# INSTITUTE OF TECHNOLOGY

## AIR UNIVERSITY

## UNITED STATES AIR FORCE

# SCHOOL OF ENGINEERING

## THESIS

**WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

OPTIMIZATION OF MANNED ORBITAL SATELLITE VEHICLE DESIGN

WITH RESPECT TO ARTIFICIAL GRAVITY

THESIS

Presented to the Faculty of the School of Engineering

Institute of Technology

Air University

in Partial Fulfillment of the

Requirement for the

Master of Science Degree

in Astronautics

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by

Benjamin J. Loret, B.S., M.B.A.

Capt                                    USAF

Astronautics

August 1961

## Preface

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A specific attempt has been made to present the information in a form that will be useful both to the design engineer who may not be well versed in human factors, and to the human-factors specialist who may not be well versed in the engineering aspects of design.

I would like to express my thanks to Captain John C. Simons and the psychologists in his section, who have been of much help in their constructive criticism of Chapter III on human factors, to Dr. Delmar W. Breuer, Professor Paul H. Keister, and Captain Homer G. Pringle, my faculty thesis advisors of the Mechanics Department, for their guidance, particularly on the subjects of rotating vehicle mechanics and engineering aspects of design, and to Dr. Frank R. Smith, of the

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The optimum vehicle configuration is established as a Modified Axially-Expanded Dumbbell, characterized by a single, cylindrical living-working compartment oriented parallel to the spin axis, counterbalanced by other vehicle components. The configuration is illustrated in the conceptual Pseudo-Geogravitational Vehicle, which has a radius of 180 feet and an operational angular velocity of 0.4 rad/sec to produce 0.9 g in the living-working compartment.

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Subject and Purpose

The subject of this study is the design of manned orbital satellite vehicles which are rotated to create artificial gravity. Human factors are given primary importance in the investigation but engineering and operational factors are also considered so that the results will have practical value. The purpose of the study is to provide specific design criteria and an optimum configuration for vehicles of this type.


Background to the Problem

One of the most serious handicaps to the engineer who attempts to design a manned orbital satellite vehicle is his inability to obtain a definite answer to the question, "Will an artificial gravity environment be necessary for the efficiency and comfort of the crew, and if so, how much "g" is necessary?" The answer to this question is unknown to the aeromedical specialists. To date the longest period of observed weightlessness experienced by man is a little over one day. Experimental data on long term effects of zero gravity on man will not be available until human-orbit times of several days and weeks are available. This capability will probably not be achieved by the United States for some time.

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Although the experts have attempted to refine their estimates, in the absence of a definite answer to the question, the design engineers have had no choice but to provide separate designs to meet either contingency. Design proposals to date have provided for either a weightless environment or a "g"-level for the vehicle based upon an educated guess at what the proper "g"-level should be.

Most satellite vehicles have been designed to optimize such parameters as mass ratios, thrust-weight ratios, booster engine performance and other critical criteria. Very little appears to have been done to optimize design with respect to artificial gravity. Dole (Ref 9:3) makes note of this gap in his recent work on the subject for the Rand Corporation. The gap is only partly explained by the lack of definite information concerning the effects on man of sustained zero-"g". Another important reason is the fact that designing for artificial gravity is an activity that falls into the province of both the engineer and the aeromedical specialist. Neither individual, except in rare cases, is sufficiently qualified in both fields to undertake the job alone.

Because the optimization of design with respect to artificial gravity has not received as much attention to date as have other aspects of space-vehicle design, it is a fertile field for investigation.

## Scope of the Investigation

The question of whether artificial gravity is necessary will not be discussed in this paper. It is assumed from the beginning that artificial gravity is either desirable or absolutely necessary. The task then becomes one of optimizing the design with respect to this criterion.

As stated earlier, human factors are given primary importance, i.e., the criteria established are those which optimize vehicle design with respect to man, his efficiency, and his comfort, in an artificial gravity environment. The placement of emphasis on human factors is not meant to imply that other factors are ignored, but rather that their consideration is restricted to only those aspects relevant to the main topic.

Finally, it will be assumed that more than a minimal-capability vehicle can be placed in orbit. The assumptions are made that

1. The vehicle can be constructed in orbit;

2. The vehicle will be a permanent installation with provision made for resupply and exchange of crew every few weeks;

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Although these assumptions imply a projection into the future, the principles derived in this investigation are applicable to the design of any manned orbital satellite vehicle which is rotated to create artificial gravity.

## Plan for the Report

The general approach is to identify the variables which affect the

rotation, to analyze the interrelationships between the variables and the human factors in order to prescribe a human-factors design envelope, and to select an optimum configuration for the vehicle based on human-factors, engineering, and operational considerations.

In accordance with the general plan, Chapter II is devoted to an analysis of the artificial gravity environment. The variables are identified and their relationship to "g"-level established. Peculiarities of the artificial gravity environment in terms of static and dynamic forces are discussed. Some figures of merit are established.

Chapter III is concerned with man's ability to maintain his orientation, his equilibrium, and his efficiency in the artificial gravity environment. Where possible, experimental evidence is used to establish permissible stress levels. Reasonable assumptions are made to establish tolerance limits in those cases where no experimental evidence is available. The definition of maximum stress under which man can still operate comfortably and efficiently establishes a human-factors design envelope and some human-factors design principles.

Further limits on vehicle design are established in Chapter IV through consideration of engineering and operational requirements. A comparison of various possible vehicle configurations in the light of human, engineering, and operational factors permits the selection of an optimum design configuration in Chapter V. The use of the parameters for future design, illustrated in a description of a Pseudo - Geogravitational Vehicle, and some comments on minimal-capability design and current proposals serve to conclude the investigation.

The final chapter, Chapter VI, contains a summary of the investigation, a statement of the conclusions derived therefrom, and some recommendations for future research.

## II. The Artificial Gravity Environment

### Creation of Artificial Gravity Through Rotation

In the weightless environment which exists in a satellite vehicle in orbit around the Earth, an artificial gravity force can be created by rotating the vehicle about some nearby axis or about some self-contained axis, as shown in Figure 1. The rotating rim of the vehicle shown in the figure continually accelerates the man inward toward the spin axis. The rim force creating this acceleration is called centripetal force (shown by the white arrow). Centrifugal force (shown by the black arrow) is an equal and opposite inertial reaction force which is



FIGURE 1. CREATION OF ARTIFICIAL GRAVITY THROUGH USE OF ROTATING VEHICLE

experienced by the man as "weight". The Newtonian expression $\bar{F} = m\,\bar{a}$ is applicable and for the case of rotation, the artificial gravity force is given in vectorial form as

$$\bar{F}_g = -\frac{\bar{\omega} \times (\bar{\omega} \times \bar{r})}{g_c} \tag{1}$$

where $\bar{F}_g$ = the artificial gravity force (centrifugal force), $lb_f/lb_m$ ("g"s per unit mass)

$$G_c \; = \; \text{the gravitational constant,} \; 32.2 \; \frac{lb_m \, ft}{lb_f \, sec^2}$$

$\bar{w} \times (\bar{w} \times \bar{r})$ = the centripetal acceleration*, $ft/sec^2$

in which $\bar{w}$ = Omega, the angular velocity of rotation[#], radians/sec

$\bar{r}$ = the perpendicular distance from the axis of rotation to the object on which the force acts, ft.

The usual reference used in discussing artificial gravity is the one-"g" value experienced by objects on the earth's surface, where the acceleration of one "g", i.e., 32.2 $ft/sec^2$, is used to express the equivalent force which will produce this value of acceleration. In this paper, the terms gravity, artificial gravity, $\bar{F}$, and "g", are all used interchangeably to represent forces or their equivalent accelerations. Various levels of artificial gravity will be expressed in terms of the standard gravity force on earth, i.e., zero point five gravity (0.5 g) is an artificial gravity force equivalent to an acceleration of 0.5 (32.2 $ft/sec^2$), or 16.1 $ft/sec^2$.

For rotation, the centrifugal force vector is seen to have a magnitude equal to $(w^2 r)/G_c$ and is always directed outward from, and perpendicular to, the axis of rotation. The variables which influence the magnitude of artificial gravity force are the angular velocity $(\bar{w})$, and the radius of rotation $(\bar{r})$, and the two may be regulated

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*The minus sign is introduced into the equation to account for the fact that the centrifugal force is an inertial reaction force which acts in a direction opposite to the centripetal acceleration.

[#]In vector notation, the angular velocity vector is defined as a vector lying along the axis of spin, with its positive direction being that in which a right-hand screw would move if it were rotated in the direction specified, and with its length proportional to the scalar magnitude of the angular velocity. For basic vector analysis, the reader is referred to Wiley (Ref 41:461) or Constant (Ref 8:3).

individually or together to achieve any desired level of gravity.

The graph of Figure 2, page 9, shows a plot of angular velocity versus radius to achieve various "g"-levels. It can be seen that for any constant angular velocity, the magnitude of gravity experienced by an object at a particular position inside the rotating vehicle varies directly as its radius from the axis of rotation. As a consequence, objects close to the axis of rotation experience a lower "g"-level than those further out. Objects at the axis of rotation will experience zero-"g", i.e., they will be weightless.

Because of its significance in terms of human factors, this "gravity gradient" which exists inside the rotating vehicle is an important design consideration.

## The Gravity Gradient

In a normal standing position on an inside rim of the rotating vehicle, a man will be oriented with his longitudinal axis perpendicular to the spin axis (Figure 3, below). His head will be at a lesser radius than his feet, hence his head will feel "lighter" than his feet.



FIGURE 3. MAN STANDING IN ROTATING VEHICLE EXPERIENCING HEAD-TO-FOOT GRAVITY GRADIENT

FIGURE 4. MAN RECLINING IN ROTATING VEHICLE EXPERIENCING UNIFORM GRAVITY

FIGURE 2. ANGULAR VELOCITY ($\bar{\omega}$) VERSUS RADIUS OF ROTATION
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## The Gravity Gradient

In a normal standing position on an inside rim of the rotating vehicle, a man will be oriented with his longitudinal axis perpendicular to the spin axis (Figure 3, below). His head will be at a lesser radius than his feet, hence his head will feel "lighter" than his feet.



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FIGURE 2. ANGULAR VELOCITY (Ω) VERSUS RADIUS OF ROTATION (r̄) TO ACHIEVE VARIOUS LEVELS OF ARTIFICIAL GRAVITY IN MANNED ORBITAL SATELLITE VEHICLES

For the reclining man (Figure 4), this gravity differential will be negligible because his entire body lies at a constant radius.

The percentage expressed as the gravity gradient between head and feet to the gravity at "floor" level varies with radius. For any radius of the floor and with the assumption of the man's height as six feet, the percentage can be expressed as

$$\frac{\Delta F_g}{F_g} = \frac{\bar{r}^2 (6)}{\bar{r}^2 \, r} (100\%) = \frac{600}{r} \% \qquad \text{for } 6 \leq r \qquad (2)$$

The restriction is placed on $\bar{r}$ because for values of $\bar{r}$ less than six feet, the axis of rotation will pass through the man's body, with the result that the portion "above" the axis of rotation will experience slight negative "g", while the portion at the axis experiences weightlessness. Such a situation is obviously unacceptable.

A plot of percentage versus radius is shown in Figure 5. A glance at the curve shows that at radii larger than 40 ft, the percentage drops to less than 15%.



FIGURE 5. GRAVITY GRADIENT (HEAD-TO-FOOT) EXPERIENCED BY A 6 FT. MAN IN ROTATING VEHICLE, EXPRESSED AS PERCENTAGE OF GRAVITY AT FLOOR-LEVEL, FOR VARIOUS VALUES OF FLOOR RADIUS
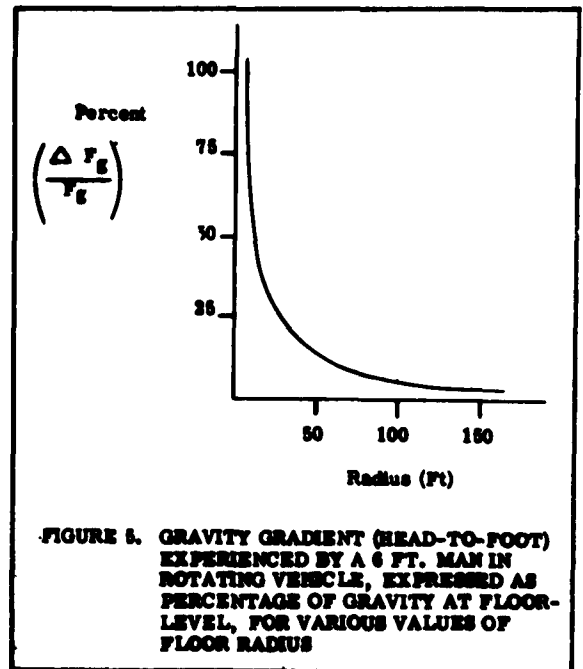
## Coriolis Effects

In addition to the artificial gravity force discussed above, a man on or inside the rotating vehicle who moves with respect to the vehicle will experience inertial reaction forces known as Coriolis forces. The

Coriolis force vector is given by the expression

$$\bar{F}_c = -\frac{2\,\bar{w}\times\bar{v}}{g_c} \qquad (3)$$

where $\quad \bar{F}_c \;=\;$ the Coriolis force, $lb_f/lb_m$ ("g"s per unit mass)

and $\qquad \bar{v} \;=\;$ the velocity of the man with respect to the rotating reference frame, ft/sec.

The magnitude of the Coriolis force, expressed in "g"s per unit

mass, is

$$F_c = \frac{2\,w\,v\,\sin\theta}{g_c}$$

where $\quad \theta \;=\;$ Theta, the angle between the $\bar{w}$ vector and the $\bar{v}$ vector, in degrees or radians.

The direction in which the Coriolis force acts is given by the normal rule for vector cross products.*

It can be seen that the Coriolis force is proportional to the magnitudes of the variables $\bar{w}$, $\bar{v}$, and $\theta$ but is independent of $\bar{r}$. The introduction of the variable $\theta$ causes the phenomenon of Coriolis Force to differ from that of centrifugal force in that while the centrifugal force is always directed perpendicularly outward (i.e.,

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*The direction of a vector cross product is given by the "right-hand rule", i.e., if the fingers of the right hand are pointed in the direction of the $\bar{w}$ vector and the hand is then rotated fingers toward palm (through the shortest angle) so that the fingers point in a direction parallel to the $\bar{v}$ vector, the right thumb will point in the direction of the vector cross product. The minus sign on the right side of equation (3) indicates that the Coriolis inertial reaction force acts in a direction opposite that indicated by the vector cross product $(\bar{w}\times\bar{v})$.

radially) from the spin axis, the Coriolis force direction and magnitude depend upon the geometric relationship between the spin axis and the relative velocity vector.

Coriolis forces will have maximum value when $\theta$ equals 90°, i.e., when the velocity vector lies in the plane of rotation (any plane perpendicular to the spin axis). Any motion in the plane of rotation can be resolved into radial and tangential components.

For radial motion, the Coriolis force will act perpendicular to the gravitational force as shown in Figure 6, below. This peculiarity results because each rung of the ladder h̰as a higher inertial tangential velocity than the one above it, the magnitude of the velocity for each rung being equal to the product of $\bar{w}$ and the radius to the rung.



FIGURE 6. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN RADIAL DIRECTION INSIDE ROTATING VEHICLE
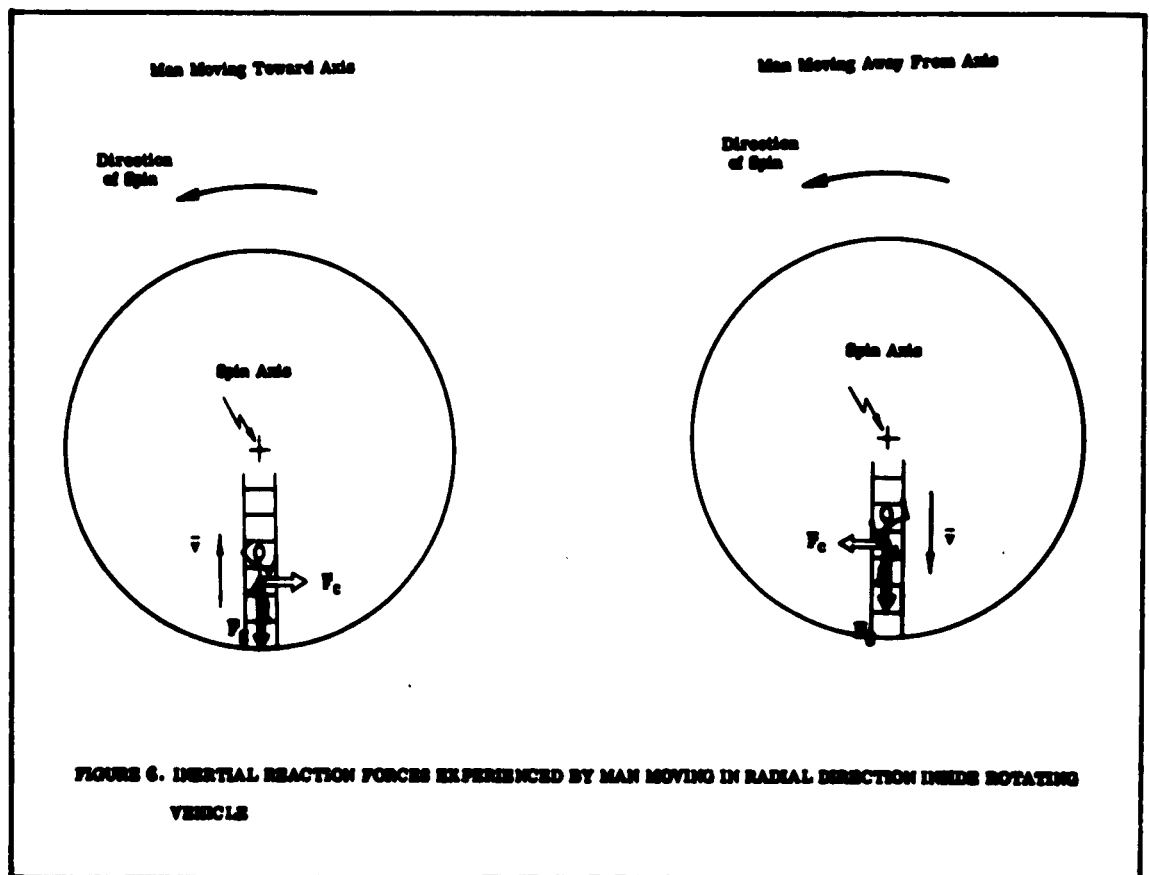
Therefore, the man climbing the ladder (Figure 6, left) must decelerate

to the left to match his tangential velocity to the tangential velocity

of the next higher rung. He does this by pulling himself to the left

as he climbs. The deceleration gives rise to an inertial reaction

force, the Coriolis force, which acts to the right as shown. The

converse analysis is applicable for descent from the spin axis (Figure

5, at al).

For tangential motion, the Coriolis force will act parallel to the

centrifugal force, adding to it if the direction of motion is "with"

the spin, and opposing it if the direction of motion is "against" the

spin (Figure 7). Thus a man walking tangentially with the spin will

feel "heavier", while a man walking in the opposite direction will feel

"lighter". In effect, a tangential velocity acts to increase or decrease



FIGURE 7. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN TANGENTIAL DIRECTION INSIDE ROTATING VEHICLE
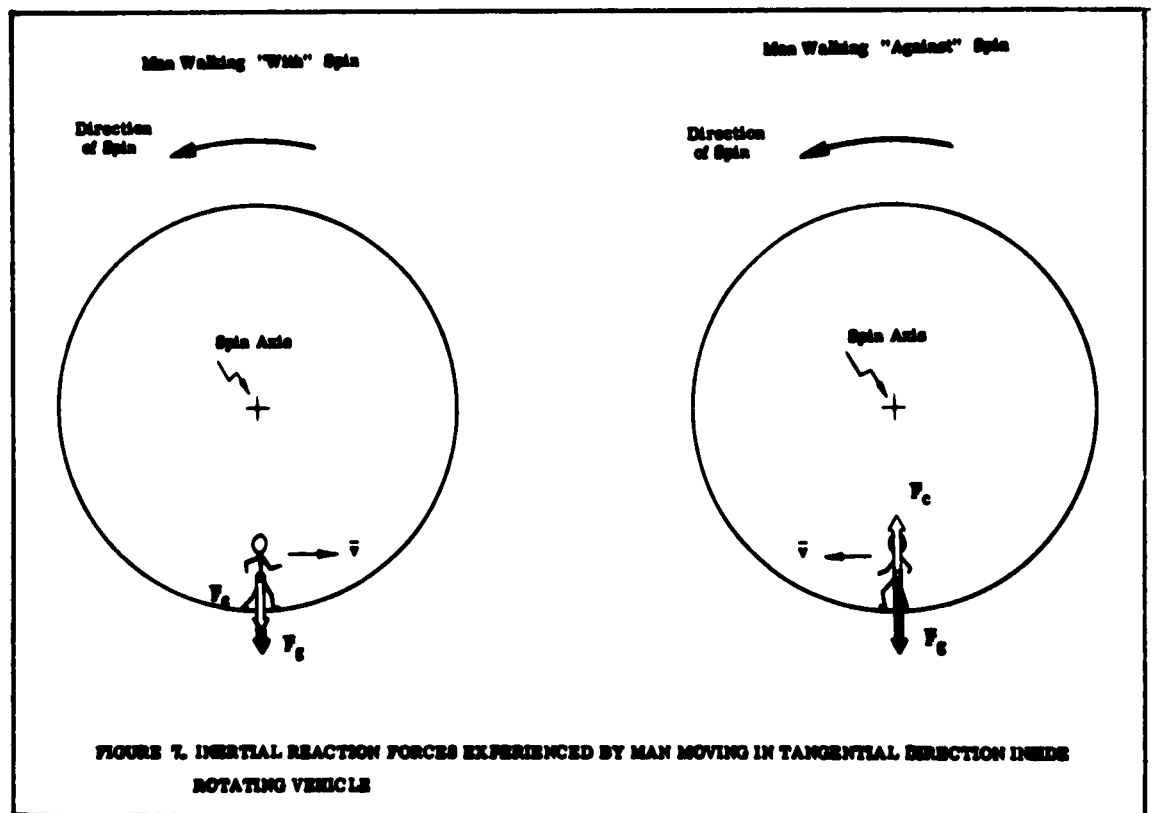
the effective (inertial) angular velocity; hence a man walking tangentially can be considered to be subject to an artificial gravity force equal to $(w_{effective})^2 r/g_c$, where $w_{effective} = (w \pm \frac{v}{r})$. An expansion of the squared term gives rise to the artificial gravity force consisting of two positive terms -- the normal artificial gravity force $(+w^2 r/g_c)$, due to vehicle rotation, and an additional artificial gravity force $(+v^2/rg_c)$, due to the relative velocity of the man around the inside rim of the vehicle with respect to the vehicle -- and to the Coriolis force $(\pm 2wv/g_c)$, the sign of which depends on whether the direction of walk is with or against the spin.

No Coriolis forces will exist when $\theta = 0°$ or $\theta = 180°$, i.e., when the velocity vector is parallel to the spin axis.* A man walking parallel to the spin axis with constant velocity will therefore in general experience only the local gravity force (Figure 8).#



FIGURE 8. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN AXIAL DIRECTION IN ROTATING VEHICLE

The Coriolis force experienced by a man moving along any random path inside the rotating vehicle can be calculated through resolution of the motion along the orthogonal system formed by the radial,
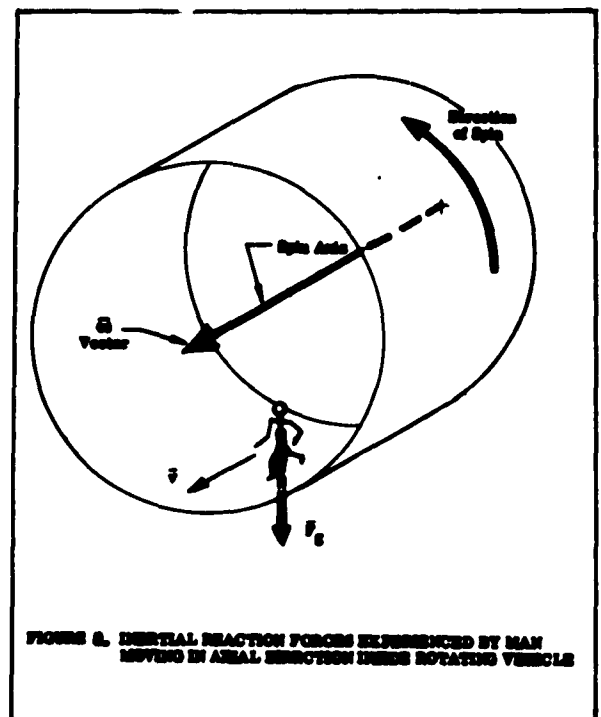
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tangential, and spin axes. The superposition of the calculated effects along each axis will provide a net resultant Coriolis force. The contributions of Coriolis forces due to the radial and tangential components of velocity added to the local centrifugal force will give the total resultant force on the man due to rotation and movement. As seen above, the component of velocity along the axis of rotation causes no contribution to the net total force experienced.

The path followed by any object thrown, tossed, or "dropped" inside the rotating vehicle can be calculated with respect to any desired reference frame by use of analytical dynamics (Ref 26).

Combined Effects of Coriolis Forces Plus Artificial Gravity

It is evident from the preceding analysis that the force environment to which man is subject inside the rotating vehicle may differ significantly from the gravitational environment to which he is subject on earth, depending on the values selected for the variables which influence the artificial gravity environment, i.e., $\overline{w}$ and $\overline{r}$.

Radial motion, which superimposes side forces upon the artificial gravity force, is one peculiarity man will experience in the rotating vehicle. With respect to this peculiarity, a figure of merit which is used in vehicle design is the ratio of the side force to the artificial-"g" force for varying radius (Ref 23:49).

For a man climbing radially toward the axis of rotation with constant velocity relative to the rotating frame, the side force will remain constant while the artificial gravity force decreases. The ratio of the side force to the artificial gravity force is given by the following equation:

$$\frac{F_c}{F_g} = \frac{2\,\bar{w}\,v}{\bar{w}^2\,r} = \frac{2\,v}{\bar{w}\,r} \qquad\qquad\text{(4)}$$

Since for constant $\bar{w}$, the ratio varies inversely as radius, the effect is most significant in the vicinity of the spin axis. An appreciation of the magnitude of this effect can be gained by considering a specific case. Assuming that an angular velocity of 0.8 rad/sec is specified to provide a one-"g" environment at a vehicle radius of 50.3 feet, and assuming a radial transport velocity for a man of 2 ft/sec, the radius at which the man experiences a side force equal to one half the local gravity force as he approaches the spin axis is calculated to be 10 feet. At this radius he will be subject to a local gravity force of about 0.2 g and a side force of 0.1 g.

It is evident from this example that the direction of the resultant force vector can vary significantly for radial motion near the spin axis and is therefore an important consideration in human-factors design. The importance of this ratio will depend on the value of $\bar{w}$ and the configuration of the vehicle, which in turn will both be influenced by man's ability to tolerate this particular stress.

The variation in artificial gravity as man walks tangentially in the plane of rotation is a second peculiarity of the artificial gravity environment. A figure of merit which reflects this stress is the percentage change in total force experienced by the walking man from that experienced by the stationary man (Refs 25:287; 9:8). The formula is similar to that used for radial motion except that an indoor walking velocity of 4 ft/sec is assumed and the ratio is given as a percentage, i.e.,

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$$\frac{\Delta F_g}{F_g} = \left[\pm \frac{2\,w\,(4)}{w^2\,r} + \frac{(4)^2}{w^2\,r^2}\right] 100\% = \left[\pm \frac{800}{wr} + \frac{1600}{(wr)^2}\right] \% \qquad (5)$$

where the plus or minus reflects the direction of walk.

The effect is seen to be inversely proportional to the first and second powers of the quantity $(wr)$, i.e., the linear tangential velocity of the floor on which the man walks. The graph of Figure 9, on the following page, shows the approximate percent variation in gravity versus angular velocity for various values of floor-level radius, assuming a walking velocity of 4 ft/sec. For convenience, "g"-levels corresponding to the various values of radius and angular velocity for the stationary man are superimposed on the basic graph.

For simplicity of presentation, the second term of equation (5) is not included in the graph of Figure 9. Since the contribution from the second term is relatively small (particularly for large values of $wr$), the graph has sufficient accuracy to be of value in obtaining the change in artificial gravity for tangential walking in any given vehicle. The precise percentage change may be obtained by algebraically adding the increment $1600\%/(wr)^2$ to the plus or minus value obtained from the graph.

The use of the graph and its accuracy may be illustrated by an example. With the same data used previously, i.e., for an angular velocity of 0.8 rad/sec and a radius of 50.3 ft, the percentage variation in gravity for tangential walking is found from the graph to be about 20%. The value of local gravity can also be taken from the graph as being one "g". Therefore the man will experience (100 + 20)% of one "g",
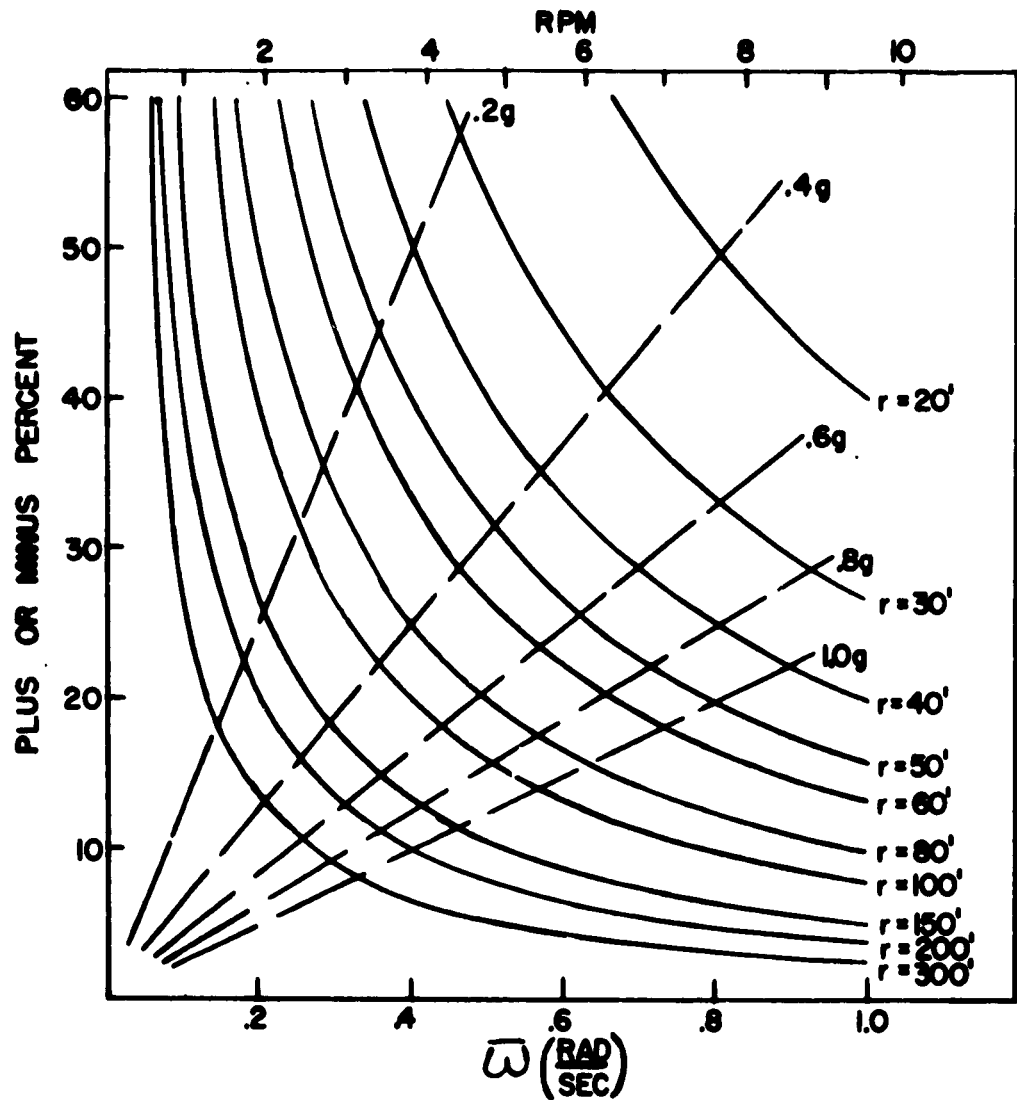
NOTE: For walk in direction of spin (+ %), indicated value is slightly low.
For walk in direction opposite spin (- %), indicated value is slightly high.

FIGURE 9. APPROXIMATE PERCENT CHANGE IN ARTIFICIAL GRAVITY
EXPERIENCED BY MAN WALKING WITH TANGENTIAL
VELOCITY OF 4 FT/SEC INSIDE ROTATING VEHICLE
VERSUS ANGULAR VELOCITY (ω) OF VEHICLE, FOR VARIOUS
VALUES OF FLOOR-LEVEL RADIUS (r̄). ARTIFICIAL
GRAVITY LEVELS CORRESPONDING TO ANGULAR
VELOCITY AND FLOOR-LEVEL RADIUS FOR STATIONARY MAN
SHOWN BY DASHED LINES.

or 1.2 g when he walks in the direction of spin, and $(100 - 20)\%$ of one "g", or 0.8 g when he walks against the spin. The exact values are calculated to be $+ 20.8\%$ or 1.208 g, and $- 18.8\%$ or 0.812 g, respectively.

The establishment of tolerance limits of man to this variation in artificial gravity as well as to the other peculiarities of the rotating-vehicle environment will permit the establishment of a design envelope within which the variables $\bar{w}$ and $\bar{r}$ must lie. The establishment of the human-factors design envelope is the subject of the next chapter.

III. <u>The</u> <u>Influence</u> <u>of</u> <u>Human</u> <u>Factors</u> <u>on</u> <u>Design</u>

In his terrestrial environment, man is subject to a one-"g" force which always acts perpendicular to the earth's surface. While he is subject to minute variations in gravity from place to place, and to Coriolis forces due to the earth's rotation, these variations are so minute that they are below the threshold of man's senses.* Such is not the case inside the rotating vehicle where variation in artificial gravity and Coriolis forces may be of sufficient magnitude not only to disturb man but also to incapacitate him.

At what values these variations become significant or intolerable is largely a matter of conjecture. Since it is difficult, if not impossible, to create on earth the conditions which exist in a rotating space vehicle, only a bare minimum of experimental evidence is available upon which tolerance limits can be based. The best that presently can be done is to evaluate man's tolerance on the basis of this meager evidence. In some cases where evidence of man's tolerance to a particular combination of stresses is not available, an attempt at extrapolation of data from related experiments may be made, but only with full knowledge that the results may not be precise. In other cases, where no evidence at all is available, assumptions must be postulated.

The fact that the derived design criteria may not be exact should

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*The angular velocity of the earth about its axis is $7.29 \times 10^{-5}$ rad/sec. Maximum variation in gravity value over the earth's surface is less than 1% from standard value.

not bar an attempt to prescribe at least a rudimentary human-factors
design envelope and some general principles upon which vehicle design
can be based.

## General Considerations

As far as man is concerned, the ideal vehicle environment is one
which would duplicate that on earth. Such an environment could be
closely approximated using a vehicle with an extremely small value
for angular velocity and the correspondingly large radius necessary
to produce one "g". But a glance at Figure 2, page 9, shows that
as $\bar{w}$ approaches zero, the radius required to achieve any "g"-level
approaches infinity. As an example, for an $\bar{w}$ of 0.01 rad/sec, the
radius required to provide one "g" is 61 miles. The construction of
such a vehicle is clearly impractical.

Practicality dictates the use of a smaller radius of rotation,
which necessitates the use of higher values of $\bar{w}$. But at some upper
limit of $\bar{w}$, Coriolis forces would be of sufficient magnitude to produce
noticeable effects; hence the environment would be something less than
ideal.

The designer is thus confronted with a dilemma. On the one hand,
practicality dictates the use of as small a radius as possible. On
the other, the corresponding increase in $\bar{w}$ acts to distort the desired
ideal environment. The degree to which the environment may be distorted and
still be acceptable to a human is the crux of the design problem.

Because it is the decrease in radius and the increase in angular
velocity which distort the gravitational environment, the inner limit

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of $\bar{r}$ and the upper limit of $\bar{w}$ at which man can operate efficiently become parameters of interest. Since the artificial gravity level is intimately connected to these variables, the maximum and minimum permissible values of artificial gravity are additional parameters of interest. Thus the human-factors design envelope will be an open figure prescribed by : minimum permissible $\bar{r}$, maximum permissible $\bar{w}$, and the upper and lower limits on "g". The figure will be an open one because there is no maximum permissible value of $\bar{r}$ or minimum permissible value of $\bar{w}$, the only limit being one of practicality.

In the process of establishing the human-factors design envelope, general principles may also be derived which, if observed in engineering design, will result in a vehicle gravitational environment which more nearly simulates the terrestrial one.

## The Human Mechanism for Spatial Orientation

Man maintains his spatial orientation through integration of information concerning the environment which is transmitted to his brain through his senses. Some discussion of the mechanism by which man senses his environment will assist in establishing his tolerance limits to the unusual effects of the rotating-vehicle environment.

The sensory mechanism, referred to by Campbell (Ref 5:66) as the "orientation triad", consists of the eyes, the vestibular organs located in the inner ear, consisting of the semicircular canals and the otoliths, and finally, the mechanoreceptors located in the muscles, tendons and joints. Of these, the eyes are the primary sensors and in the absence of any other stimuli, as in weightlessness, they provide sufficient information to permit orientation.

Of particular significance is the fact that both the otoliths and the semicircular canals operate on inertial principles. The otoliths sense linear and gravitational accelerations while the semi-circular canals sense angular accelerations. Therefore any accelerations (forces) which are applied to the organs act as stimuli. The impulses which result from the stimuli are sent to the brain, where they are integrated with impulses sent from the eyes and the mechanoreceptors to provide man with spatial orientation and balance.

Under normal conditions on earth, maintenance of orientation and balance is a simple matter. The one-"g" force acting on the otoliths causes impulses to be sent to the brain which are in consonance with what man sees and feels. But under complex rotations, accelerations, and motions, which occur aboard ship in rough seas, for example, conflicting messages are sent to the brain. The results, some of which most people have experienced at one time or another, are dizziness, loss of orientation and balance, the appearance of visual illusions, nausea, and in severe cases even collapse (Ref 4:490).

The manner in which the conflicting impulses interact with one another, and the influence of other psychosomatic disturbances such as anxiety, fear, and fatigue on these interactions to produce detrimental effects is not completely understood, as is evidenced by the writings of authorities on the subject.[*] Because overstimulation of the vestibular apparatus appears to be the primary factor involved, the term "canal sickness" has been used to describe these symptoms (Ref 18:55).

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[*] For information on the operation and functioning of the triad, illusions, spatial orientation, and related subjects, the reader is referred to Refs 6, 13, 14, 15, 16, 19, 20, 21, 32, 35, 36, 37, 38, and 40.

## Design Limitations Due to Canal Sickness

Man's response to the stimulus on the triad, and particularly on the inner ear, caused by the complex dynamic force environment peculiar to the rotating vehicle, is probably the most critical of all human factors in vehicle design.

The changing forces to which man's body is subject while moving in the vehicle are also applied to the otoliths and semicircular canals. The changing gravity forces and Coriolis forces which result from locomotion inside the vehicle or due to movement, rotation, or cocking of the head, all act on the vestibular mechanism. Such overstimulation is obviously conducive to canal sickness. Because of the deterioration in human performance and comfort which result, special attention must be given to vehicle design to prevent or minimize the possibility that Coriolis forces will produce canal sickness.

The results of some experimental studies may be used to obtain stress limits. While the experiments did not create the exact conditions which would exist in the rotating vehicle, they do provide some conclusions upon which stress tolerances may be estimated.

In the experiments performed by Graybiel, Clark, and Zarriello (Ref 18) at the U.S. Naval School of Aviation Medicine at Pensacola, Florida, subjects were placed in a 15-ft-diameter, 7-ft-high room centered on a centrifuge. The room was rotated at constant angular velocity for 48 hours during which time the subjects were observed not only while they performed various tasks but also during "off-duty" hours. Separate runs were made at 1.71, 2.22, 3.82, 5.44, and 10.00 RPM to provide experimental data for a range of rotation rates.

Since the subjects were within 8 feet of the axis of rotation, the sideward centrifugal force to which they were subjected, compared to the normal one "g" they experienced vertically, was not considered to be significant. Therefore, the primary stimuli were considered to be the Coriolis forces which acted on the canals during the experiment.

The general findings of the experiment may be summarized as follows (Ref 18:71):

(1) Head motion parallel to the axis of rotation or head rotation about that axis produced no ill effects. (Note: This was to be expected since practically no Coriolis forces would act on the canals for this type motion).

(2) Head motion in any other direction or head rotation about any other axis caused the canals to be stimulated. Maximum stimulation occurred when the head was rotated about an axis perpendicular to the spin axis. (Note: Maximum Coriolis forces act on the canals for this type motion).

(3) Illusions and symptoms of canal sickness such as malaise, apathy, nausea, and incapacity to perform assigned tasks were experienced by various subjects at various times during each run.

(4) There were marked differences in susceptibility to canal sickness among the subjects but even those subjects least susceptible to canal sickness became ill and were unable to carry out tasks at 10.00 RPM. It is interesting to note that the control subject, whose vestibular apparatus was permanently inoperative due to previous ear illnesses, experienced none of the symptoms of canal sickness.

(5) There was some adaptation to the environment after different periods of time for different subjects.

In a report on gravity problems in manned space stations, Clark

and Hardy (Ref 7:110) comment on an experiment performed on the centrifuge at the Naval Aviation Medical Acceleration Laboratory at Johnsville, Pa., which provides numerical data on stress limits for canal sickness.

In a study of a subject rotated in a centrifuge for 24 hours at 2 g, with an angular velocity of one rad/sec, it was determined that head rotation of 0.06 rad/sec about an axis perpendicular to the spin axis resulted in the onset of visual illusions. Any such head rotation at 0.6 rad/sec resulted in nausea.

Although the effect of the 2-g environment on these figures could not be determined, and although the figures are based on only one subject, Clark and Hardy tentatively conclude that the maximum permissible magnitude of the vector cross product of head angular velocity with vehicle angular velocity, if illusions are to be avoided, is less than $0.06 \text{ rad}^2/\text{sec}^2$; i.e., $\left| \bar{w}_{head} \times \bar{w} \right| < 0.06 \text{ rad}^2/\text{sec}^2$. Pursuing the analysis a step further, Clark and Hardy indicate that to permit normal head rotation in a rotating vehicle, for which head rotation rates might be as high as 5 rad/sec, the maximum permissible angular velocity for the vehicle should be 0.01 rad/sec. To permit the use of any higher $\bar{w}$ for the vehicle, they propose that prisms, mirrors and/or restraining devices be used to keep head rotation rates at low values.

If the maximum limit for $\bar{w}$ of 0.01 rad/sec is to be observed, the required radius to provide one "g", as seen earlier, is an impractical 61 miles. To lessen the radius would require increasing $\bar{w}$ above that which is desirable from an environmental viewpoint, but there seems to be no other acceptable choice.

Dole (Ref 9:11) selects a limit of "less than about 4 RPM" as an upper limit for $\bar{w}$ based primarily on Graybiel's study. An upper

limit on $\bar{w}$ in the range of values around 4 RPM appears to be a realistic
compromise between what is desirable from a human-factors viewpoint
and what is at least practical from an engineering viewpoint.
Accordingly, an upper limit of 0.4 rad/sec is established for $\bar{w}$.
The limit is superimposed on the basic $\bar{w}$ versus $\bar{r}$ plot of Figure 10,
page 28.

If the formula established by Clark and Hardy is valid, an $\bar{w}$
of 0.4 rad/sec would permit a maximum rate of rotation of the head
about an axis perpendicular to the $\bar{w}$ axis of about 0.15 rad/sec.
This restriction appears to be severe when compared to normal head
rotation rates of up to 5 rad/sec. But the evidence upon which the
0.01 rad/sec limit is based is not conclusive. There is some
justification to accept the figure as being conservative since the
experiment was not conducted under ideal conditions, i.e., the subject
was under a 2-g linear stress during the experiment. Further, the
Graybiel findings indicate that through proper selection of crew
members and the fact that adaptation to the rotating environment
does occur, the limit of 0.01 rad/sec might be revised upward. These
factors support the conclusion that while the selected upper limit of
0.4 rad/sec for $\bar{w}$ is not ideal, the difference between this limit and
that set by Clark and Hardy is not as extreme as it appears.

The degree to which the crew member will in fact be affected by
canal sickness can be minimized through proper design. As noted above,
it is the cross product of head $\bar{w}$ and vehicle $\bar{w}$ which is involved.
It is duly noted by Clark and Hardy and corroborated by Graybiel, that
if the head rotation takes place about an axis parallel to the spin axis,
the vector cross product is zero; hence there is minimum tendency for canal

HUMAN FACTORS DESIGN LIMITS

FIGURE 10. HUMAN-FACTORS STRESS LIMIT CURVES SUPERIMPOSED ON PLOT OF ANGULAR VELOCITY (Ω) VERSUS RADIUS OF ROTATION (r̄) TO ACHIEVE VARIOUS LEVELS OF ARTIFICIAL GRAVITY IN MANNED ORBITAL SATELLITE VEHICLES
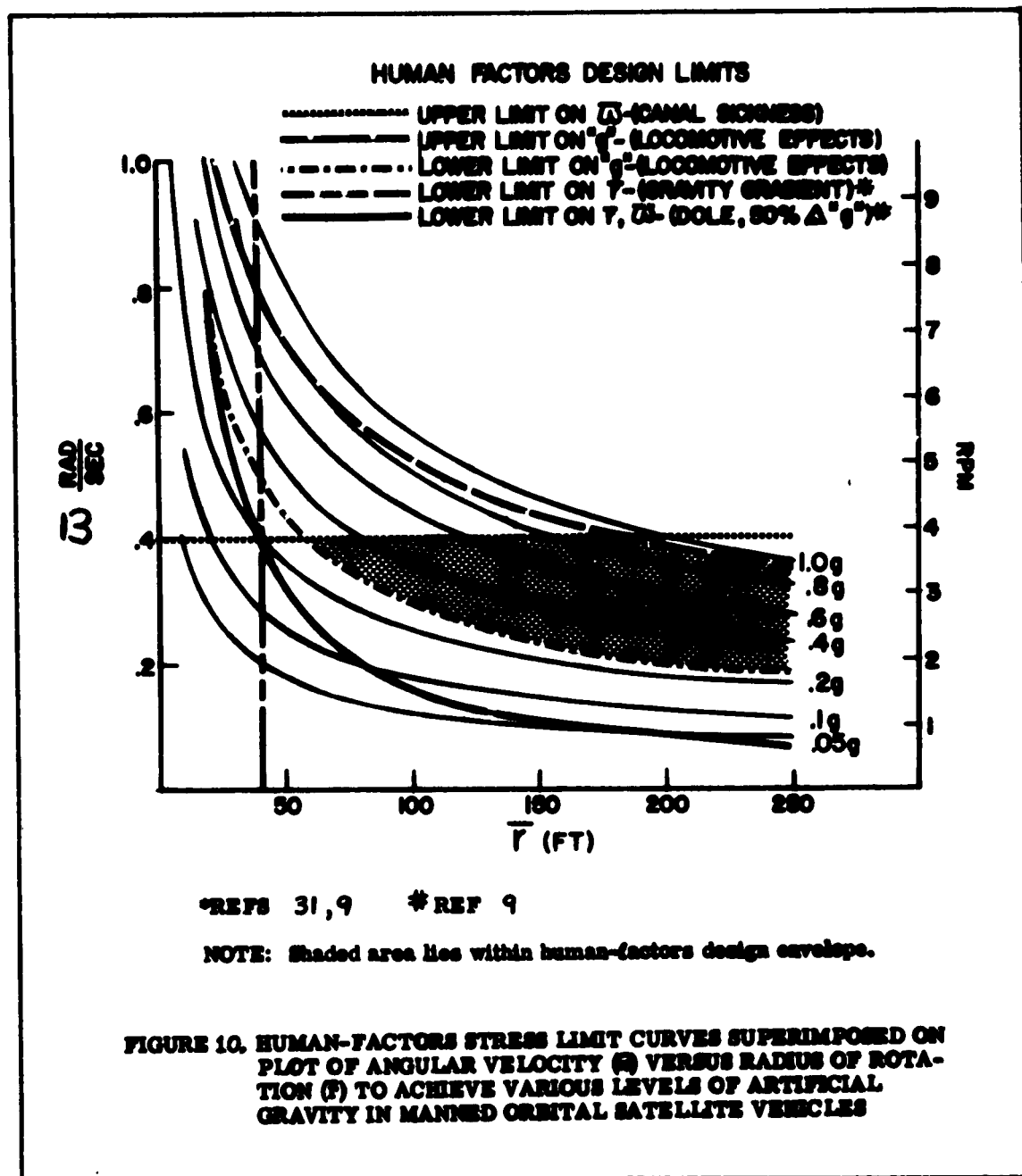
sickness to occur.  From a design viewpoint, then, the crew station

positions in the vehicle should be oriented so that the axis about

which head rotation would occur most frequently is parallel to the vehicle

spin axis.

Because he lives in a "flat" environment, man most frequently

rotates his head about his longitudinal axis, i.e., left-right.

Unfortunately, as a glance at Figure 1, page 5, will show, any

standing or sitting position in the rotating vehicle places man's

longitudinal axis perpendicular to the spin axis.  There is no way

to avoid this situation.  Thus the head rotation normally used most

by man on earth is the rotation which must be minimized in the vehicle.

Man will have to learn to restrict the angular velocities at which

he turns his head in the left-right direction and substitute as much

left-right eye movement as possible.  In fact, the substitution of

eye movement for head rotation was precisely what the subjects in the

rotating-room experiments unconsciously learned to do (Ref 18:67).

Although it is impossible to orient man inside the rotating

vehicle so that he can sit or stand normally and make normal left-right

head movements, an advantage may be gained by orienting the crew station

position so that when man is in his normal position, his lateral axis,

i.e., an axis through both his ears, will be parallel to the spin axis.

This will permit maximum up-down rotation of the head with minimum

Coriolis effects on the canals.  In observance of this principle, it

follows that the instrument display console at which the man works

should have an up-down rather than a left-right orientation.  The

console and controls should be designed so that in performance of

duty-station tasks a minimum of left-right head movement is required.

Similarly, assuming that
most head rotation while
in bed would occur about
man's longitudinal axis,
the crew bunks should be
oriented axially. Figure
11 shows the geometric
relationship which
should exist between the
designated axis of the
crew member and the spin
axis of the vehicle for
both on-duty and off-duty
stations.
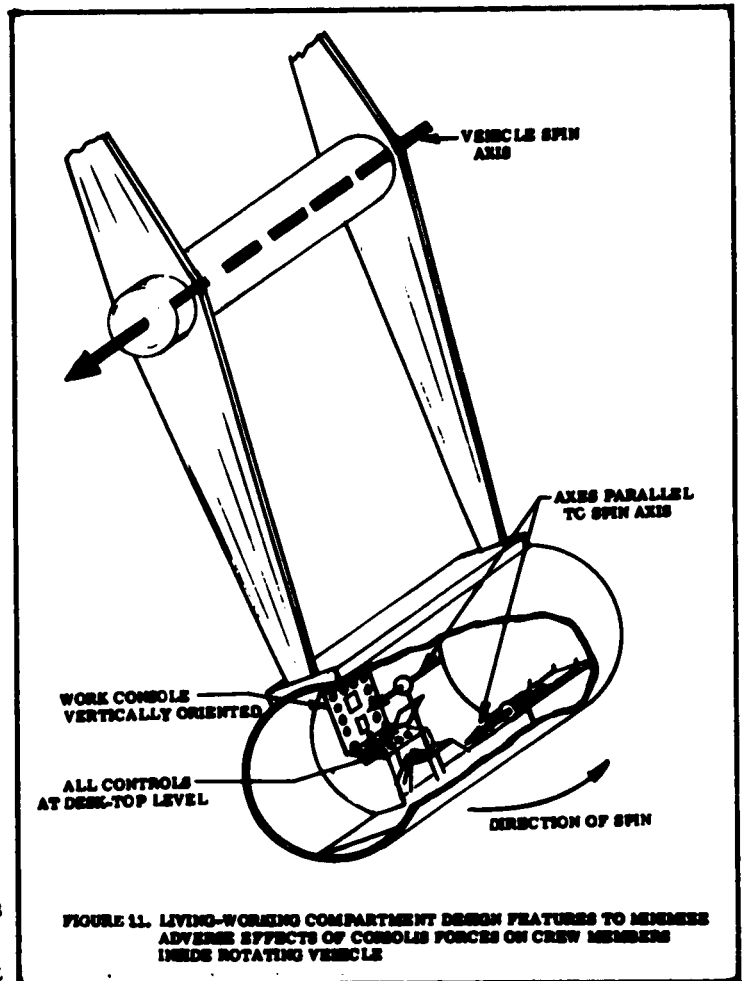
No crew duty stations
should be oriented so that



FIGURE 11. LIVING-WORKING COMPARTMENT DESIGN FEATURES TO MINIMIZE ADVERSE EFFECTS OF CORIOLIS FORCES ON CREW MEMBERS INSIDE ROTATING VEHICLE

the lateral axis lies along a tangential axis, for under this orientation both up-down and left-right head rotations would result in stimulation of the vestibular apparatus by Coriolis forces.

## Establishment of the Upper Limit for Artificial Gravity

Some writers on the subject have considered values for the upper limit in excess of one "g". Dole (Ref 9:12) includes 1.5 g as the upper "g"-limit. Kramer and Byers (Ref 23:47) also mention the possibility of a requirement for a "g"-level above one. This requirement would appear to be necessary only for the purpose of preconditioning a space crew prior to landing on a planet or other celestial body whose surface gravity level is greater than that on earth. Since at best this requirement

lies in the remote future, it appears reasonable to select an upper

limit of one "g". The upper limit is therefore prescribed by the

requirement that at no time at any position in the vehicle should the

crew member experience more than one "g".

This basic limitation has further design implications because

additional forces act when motion takes place tangentially in the

direction of spin. Since the "g"-force increases due to this motion,

it would be possible for a man in a vehicle rotated to provide one

"g" to experience more than one "g" if he were to walk tangentially

in the direction of spin. In order to permit him to walk tangentially

in the direction of spin without exceeding the basic one-"g" limit,

the ambient "g"-level of the vehicle must be lower. This lower value

sets the upper limit on artificial gravity.

For an assumed walking velocity of 4 ft/sec and for any given

radius of rotation, the upper limit on "g" may be calculated.

Assuming an 80-ft radius vehicle and a maximum permissible "g"-level

of one for the walking man, the magnitude of $\bar{w}_{effective}$ can be computed

as

$$w = \sqrt{\frac{g_c}{r}} = \sqrt{\frac{32.2}{80}} = 0.635 \text{ rad/sec}$$

The corresponding linear velocity at floor level is

$$wr = 0.635 \, (80) = 50.80 \text{ ft/sec}$$

The maximum permissible linear velocity at floor level for the vehicle

will equal the effective linear velocity for one "g" less the walking velo-

city of the man, i.e.,

$$(wr)_{\text{permissible for vehicle}} = (wr)_{\text{effective}} - v_{\text{man}}$$

$$= 50.80 - 4.0 = 46.80 \text{ ft/sec}$$

The corresponding value of vehicle $\bar{w}$ is given by

$$w = \frac{v \, r}{r} = \frac{46.80}{80} = 0.585 \text{ rad/sec}$$

and the maximum permissible "g"-level for the vehicle is

$$F_g = \frac{v^2 \, r}{g_c} = \frac{(0.585)^2 \, 80}{32.2} = 0.85 \text{ g}$$

Thus, a crew member in this vehicle could move tangentially in the direction of spin at normal walking speed without exceeding the one-"g" limit. He would experience 0.85 g when stationary.

The upper "g"-limit curve showing limiting values of "g" for all values of $\bar{r}$ is shown on the graph of Figure 10. As might be expected, the curve diverges from the one-"g" curve at small values of radius, where the high values of $\bar{w}$ cause significant Coriolis effects, and approaches the one-"g" curve at large values of radius, where the Coriolis effects are comparatively negligible.

The basis for the establishment of the one-"g" limit is sound. The lowering of the limit due to Coriolis effects is to some extent arbitrary. It might well be argued that once the man becomes accustomed to the ambient "g"-level, the increase in "g"-level experienced when walking tangentially in the direction of spin will be an added burden regardless of whether or not the total exceeds one "g". But since

from a human factors viewpoint the difference between the two limits, except at very small $\bar{r}$, is probably negligible, and since engineering practicality favors its selection, the lower value is a useful limit, the argument above notwithstanding.

Establishment of the Lower Limit for Artificial Gravity

Many design proposals have specified quite low values of artificial gravity. The low levels selected reflect one or more of the following considerations:

(1) Belief that small values of artificial gravity are sufficient from a human-factors viewpoint;

(2) A requirement for practicality and simplicity, particularly for the minimal-capability vehicles of the immediate future; and

(3) Desire for a low level of "g" for convenience, i.e., to keep objects in place, to permit use of conventional plumbing, and to make use of natural convection, etc.

Recent in-flight experiments which have been conducted by the Aerospace Medical Laboratory personnel at Wright-Patterson Air Force Base, Ohio, indicate that from a human-factors viewpoint a lower limit of 0.2 g should be established. The experiment involved an evaluation of the ability of a man to walk unaided under various levels of sub-gravity. The sub-gravity levels were obtained by flying a C-131 aircraft through Keplarian trajectories. Although the experiment was crude in nature due to the lack of precise instrumentation for maintaining constant sub-gravity levels close to the zero gravity value, the results conclusively indicate that man is able to walk unaided at 0.2 g.

Mr. Earl Sharp of the Behavioral Sciences Laboratory, who conducted

the experiment, has suggested in conversation with this author that the value of 0.2 g might possibly be too high but that downward refinement of the figure cannot be made until more precise instrumentation becomes available. Mr. Sharp further indicated that man can walk at zero "g", but only with the assistance of some mechanical or magnetic device.

From a human-factors viewpoint, that "g"-level at which man can walk unaided appears to be a logical choice for the lower "g"-limit. Any lower value would probably provide more an environment of convenience than one which reflects the psychophysiological requirements of man. Therefore 0.2 g is established as the lower limit for artificial gravity.

Following the same reasoning applied to the basic upper limit of one "g", the Coriolis effect for the crew member walking tangentially against the spin establishes a lower limit which is something greater than the basic 0.2-g limit. For the 80-ft-radius vehicle, the lower limit is calculated to be 0.277 g. The curve showing the lower limit for all values of radius is shown in Figure 10, page 28. As in the case of the upper limit, the modification is more significant at smaller values of radius.

If the assumption of the basic lower limit as being that minimum level of "g" at which man can walk unaided is accepted as valid, the modification of the basic lower limit due to Coriolis effects is easily justified, for under no circumstances would it be desirable for the walking man to experience a "g"-level at which he could not walk unaided.

Limitation Due to Gravity Gradient

There is no experimental evidence available on the effect of a gravity gradient on man, nor is there any non-orbital experiment which can be performed to determine man's tolerance to a gravity gradient at "g"-levels less than one. As a result, it has been necessary to assume some maximum permissible percentage of head-to-foot gravity gradient to floor-level gravity. Payne (Ref 31:101) and Dole (Ref 9:6) select an arbitrary maximum percentage of 15%; i.e., no value of radius will be used for which the gravity gradient between head and feet is more than 15% of floor-level gravity. Using equation (2) page 10, the excluded values of radius are calculated to be those less than

$$ r = \frac{600\ \%}{15\ \%} = 40\ ft $$

This assumption thus places a lower limit on $\bar{r}$ of 40 ft, as shown in Figure 10.

Other Limitations Due to Coriolis Effects on Locomotion

A consideration of Coriolis effects on locomotion from a human-factors viewpoint can best be analyzed by considering the effects for each of the three components of motion: radial, tangential, and axial, as was done in Chapter II.

For radial motion in the vicinity of the axis of rotation, the distortion of the gravitational environment due to the change in resultant force both in magnitude and direction, as discussed in Chapter II, would probably cause the onset of illusions (Ref 17:507) and mental confusion.

Radial transport across the axis of rotation would be particularly stressful since the direction of "down" would reverse. The 180-degree change in body position would have to be performed in the vicinity of the axis. Because of the myriad of rapidly changing stimuli to the vestibular apparatus which would accompany this maneuver, it is clear that radial transport across the axis of rotation, or even stationary activity at the rotating axis, could probably not be tolerated unless the "hub" of the vehicle were non-rotating, with provision made for transfer from moving "spoke" to non-rotating hub at some minimum radius, say 6 - 10 ft.

From a design viewpoint, the minimization of the adverse effects on man of radial motion can be effected by conducting all normal activity as far away from the axis of rotation as possible ((since large radius minimizes the effect, as seen in equation (4), page 16)), by keeping radial traffic to a minimum, by precluding transport across the axis, or activity at the axis, unless the hub of the vehicle is non-rotating, and finally, by minimizing radial movement of hands, arms, legs, and feet at the crew duty stations.

Tangential motion has previously been discussed in establishing upper and lower artificial gravity limits. The change in gravity experienced by the crew member walking tangentially poses a problem in that there is no experimental evidence to indicate the ability of man to discriminate between small gradations of gravity or on the maximum permissible deviation from local "g"-level which can be tolerated without adverse psychophysiological or locomotive effects. Dole (Ref 9:8) places a maximum permissible limit of 50% variation between tangential walking and stationary gravity levels. The curve

labeled "Dole, 50% $\Delta$ g" in Figure 10 indicates the lower limits for $\bar{w}$ and $\bar{r}$ corresponding to this requirement for a walking velocity of 4 ft/sec.

For axial walking, the only peculiarity to be observed is the fact that the radial components of limb velocity will result in the application of side Coriolis forces to the limbs. But becau.e the radial velocity component of the arms and legs will be small, and because the radial motion will be reciprocating in nature, the distur- bance will probably be of the form of minor perturbatiбns of the limbs accompanying rather than hindering locomotion. As a foot is raised, for example, it will be deflected sideways by a small Coriolis force. As it is planted, the force will act in the opposite direction with the result that the foot will more or less be planted in line with the intended direction of walk. There will be some effect on the vestibular apparatus due to Coriolis forces which result from radial bobbing of the head while walking (which will also occur when walking tangentially), but in general the effects will not be as critical as those others which accompany radial and tangential motion.

Because axial motion results in the least distortion of the artificial gravity environment, it would appear that the vehicle should be designed so as to take advantage of this fact, i.e., the major dimension of the living-working compartment should be placed parallel to the vehicle spin axis.

## Results of Human-Factors Analysis

The Human-Factors Design Envelope. An examination of the tolerance limit curves superimposed on the basic $\bar{w}$ versus $\bar{r}$ graph of Figure 10, page 28, indicates that the human-factors design envelope is prescribed

on three sides by the upper "g"-limit, the lower "g"-limit, and the upper limit on $\bar{w}$ of 0.4 rad/sec. Since the other human-factors stress-limit curves lie outside the envelope, the stress limits they represent will not normally be exceeded in the living-working compartment for any operating point of $\bar{w}$ and $\bar{r}$ which lies within the envelope.

Human-Factors Design Principles. In addition to the design envelope, the general principles to be observed in vehicle design are as follows:

(1) Radial traffic should be kept to a minimum.

(2) Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is non-rotating.

(3) The living-working compartment should be located as far as possible from the axis of rotation.

(4) The compartment should be oriented so that the direction of traffic, i.e., the major dimension of the compartment, is parallel to the vehicle spin axis.

(5) Crew duty-station positions should be oriented so that during normal activity, the lateral axis through the crew member's ears is parallel to the spin axis. In conjunction with this requirement, the work console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized (Figure 11, page 30).

(6) Sleeping bunks should be oriented with their long axes parallel to the vehicle spin axis (Figure 11, page 30).

(7) The presence of confusing visual stimuli should be minimized. For example, the apparent convergence of the vertical from any two points separated tangentially should be played down by proper interior

decoration and, except for necessary observation ports, which should
be covered when not in use, the living-working compartment should
be windowless (Ref 31:102).

While not directly related to vehicle design, it is worth noting
parenthetically that proper crew selection and training can minimize
those environmental deficiencies which cannot be eliminated.
Graybiel's findings and studies made by Kraus (Ref 24) and Johnson
(Ref 22) indicate that susceptibility to canal sickness should be
included as a screening device for selection of astronauts, and that inso-
far as earthbound facilities permit, the astronauts should be pre-
conditioned to a rotating-vehicle environment.

The establishment of the human-factors design parameters
provides the basic criteria to be used to select an optimum vehicle
configuration. The next chapter is devoted to the establishment of
other parameters which will insure the selection of a configuration
that is practical and operationally suitable.

IV.  The Influence of Engineering and Operational Factors on Design

The derived human-factors parameters and principles form the basic criteria which are to be used in the selection of an optimum vehicle configuration.  But while adherence to human-factors criteria alone will provide for a satisfactory artificial gravity environment, they will not in themselves permit selection of a configuration which will be practical and operationally suitable as well.  In order to establish design criteria which will permit selection of a practical and operationally suitable vehicle, other factors must be considered.

Of primary importance among these other factors are those which may be categorized as engineering factors and operational factors. An analysis of these additional factors is a prerequisite to the establishment of comprehensive criteria which will permit selection of an optimum vehicle configuration.

## Engineering Factors

Two of the most important considerations in the overall engineering design of the vehicle are those involving structural economy and rotational stability.  Both can best be analyzed through use of a simple, idealized model of a rotating vehicle, i.e., a dumbbell.  The engineering principles which can be simply illustrated through use of the idealized model will be applicable to any rotating vehicle regardless of the complexity of its configuration.

Analysis of a Rotating Dumbbell.  The model vehicle to be used is the idealized dumbbell shown in Figure 12, on the following page.  The

dumbbell consists of two
spheres connected by a rigid
rod of negligible mass. Sphere
1, which may be considered to
be the living-working compart-
ment, the "g"-level for which
is to be specified, is of mass
$m_1$. Mass $m_1$, for simplicity,
is considered to be a point
mass acting at the center of
the sphere. Similarly,
Sphere 2, which may be con-
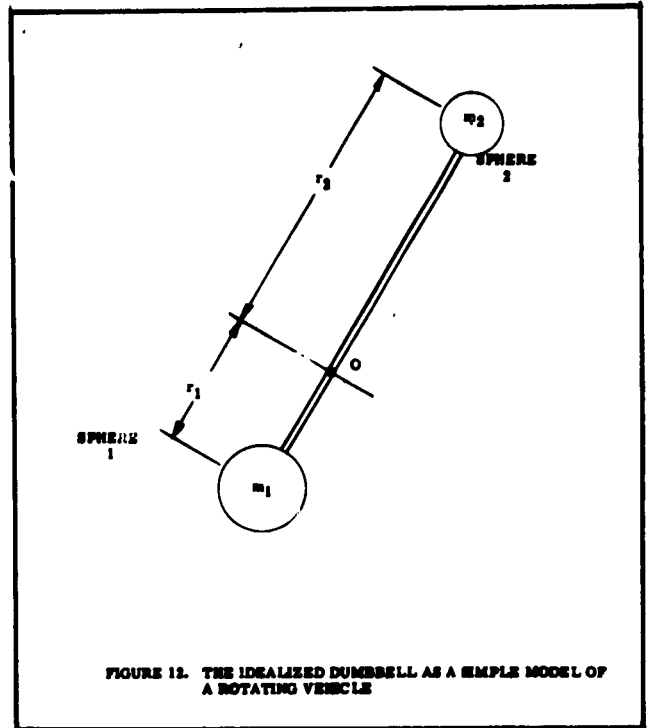


FIGURE 12. THE IDEALIZED DUMBBELL AS A SIMPLE MODEL OF A ROTATING VEHICLE

sidered to be the countermass, is of mass $m_2$. The vehicle is to be
rotated about an axis perpendicular to the rod through point O. Point O
is selected a distance $r_1$ from the center of Sphere 1 so that the
desired artificial gravity level will exist at Sphere 1 when the vehicle
is rotated at some specified value of $\bar{w}$. The distance $r_2$ from the center
of Sphere 2 to point O is adjustable.

The total centrifugal force experienced by Sphere 1 is calculated
to be $F_{g1} = m_1 r_1 w^2 / g_c$, which equals the tension in the rod. In
order to maintain this tension, an equal and opposite force must act
at point O. This equivalent force is obtained as the centrifugal force
acting on Sphere 2 due to its rotation about point O, i.e., $F_{g2} = m_2 r_2 w^2 / g_c$.
if, as in this case, $r_1$, $m_1$, and $m_2$ are specified, then the distance $r_2$
must be such that $F_{g2} = F_{g1}$, i.e., $m_2 r_2 = m_1 r_1$. This equality has
important implications in vehicle structural design and rotational
stability.

Distribution of Vehicle Mass for Structural Economy. In the ideal model, the connecting structure (the rod) has been assumed to be massless and of infinite strength. But the connecting structure of an actual vehicle will have not only mass but finite strength. The mass and the strength of the connecting structure must obviously be taken into account in design.

In the actual vehicle, the mass of the connecting structure will also be subjected to centrifugal force, which will differ at each point along the structure depending on radius. The total force acting along the massless rod was seen to be constant. In the actual case the tensile force acting at each point of the structure will vary. At any point the total force will equal the centrifugal force acting on the sphere plus the centrifugal force which acts on the mass of that part of the structure outboard from the point in question. The tension in the connecting structure is thus seen to vary inversely with radius, with maximum tensile force acting at point O, where it is equal to the centrifugal force acting both on Sphere 1 and the entire length $r_1$ of the connecting structure. This same analysis is applicable to the countermass and its connecting structure.

It is evident that radial distribution of mass in the vehicle is extremely important in design for structural economy. Because centrifugal force varies directly as radius, it is apparent that in general, vehicle mass should be kept as close to the axis as possible. A structural penalty is involved any time a pound of mass is placed any further from the axis of rotation than is necessary. The penalty is severe in that each pound of mass placed at extreme radius (added to Sphere 1), for example, increases the force acting on the connecting

structure by the increment $w^2 r_1$. The penalty which is exacted involves
not only an increase in countermass but also an increase in the mass
of the connecting structures $r_1$ and $r_2$. In contrast, a pound of mass
placed at the axis of rotation, where it is weightless, requires a bare
minimum of structure to keep it in place.

It is therefore clear that minimum mass must be placed at points
other than the axis of rotation if structural economy is to be
observed. It naturally follows from this basic principle that the
radius of the vehicle should be kept as small as possible.

Structural Design Principles. A glance at the human factors design
envelope, page 28, shows that the radius to the living-working com-
partment must be appreciable, the minimum being about 60 ft for an
artificial gravity level of about 0.3 g. The minimum radius which
will provide for maximum permissible "g" (about 0.9 g) is about 180 ft.
The radius of the vehicle is thus fixed by human-factors requirements
to lie somewhere between an absolute minimum of 60 ft and a probable
maximum of 180 ft. With the vehicle radius restricted by this re-
quirement, the task becomes one of the determination of design
principles which will result in the most economical structure.
Several such principles may be delineated.

The living-working compartment, which will be placed at the
outermost radius of the vehicle, should be as "light" as possible,
i.e., the compartment should consist of minimum mass. It logically
follows that all components which must not of necessity be located
within the compartment should be placed nearer to the spin axis. A
decision must be made as to which items must be readily accessible
to the crew and which may be remotely located. The decision is not

an easy one. Factors to be considered are: reliability of components, accessibility of critical equipment, the additional mass of ducting, power transmission circuitry, and perhaps shielding, which must be introduced when components are remotely located, and others. Some obvious cases of components which can definitely be remotely located are such massive items as storage batteries, power machinery, and storage tanks. The decision will require an optimization by trade-off between structural mass saved by remote location of each component versus the increased reliability required for remote operation and the additional mass and complexity of controls and ducting involved. Because a severe structural penalty is involved in locating mass at the extreme radius of the compartment, however, the general principle to be observed is to locate all major components remotely and to restrict the living-working compartment mass to only those essential items required for display, control, and crew safety and comfort.

In design of the countermass the most important principle to be observed is to have the countermass consist of useful mass rather than dead mass which serves merely as ballast. Various options are possible. The countermass may consist of a second living-working compartment, located at an appropriate radius, although such an arrangement would lead to an undesirable increase in radial traffic by crew members and complicate the design of the closed ecological system. A more optimum arrangement would be the use of the remotely-located components as countermass. The more massive the components the better, since the radius of connecting structure to the countermass could correspondingly be minimized. A nuclear power source would be an ideal

item to make up part of the countermass as would the other massive items previously mentioned.

In essence, the primary principle to be observed for structural economy is to minimize overall vehicle mass. Once the parameters $\bar{r}$ and $\bar{w}$ for the living-working compartment are selected, the design procedure which should be followed to minimize overall vehicle mass may be summarized as follows:

(1) The living-working compartment should consist of only those components and equipment whose ready accessibility is essential to mission accomplishment (i.e., display and control) and to crew safety and comfort.

(2) All remaining components which are not required to be located at the living-working compartment, at the axis of rotation, or at some other location to provide stability (as discussed below), should be used as countermass to minimize countermass radius.

(a) If a nuclear reactor is to be used as countermass, it should be located at the extreme radius of the countermass connecting structure with adequate shielding and separation provided between it and other countermass components.

(b) If the total useful mass is much less than the living-working compartment mass, so that an extremely long connecting structure is required, it may be more economical to use some deadweight countermass to keep countermass radius small. Some of the variables involved in the tradeoff would be: the relative masses of the living-working compartment, the countermass, and the mass-per-unit-length of the connecting structure; nuclear shielding mass and separation

distance to other components; bending loads to which the vehicle would be subject; complexity and mass of ducting and circuitry involved in remote location of components; etc.

Rotational Stability Requirements. Once a particular radius of rotation for the living-working compartment is selected, that radius must remain constant if a constant "g"-level is to be maintained in the compartment. The requirement may be illustrated through consideration of the idealized dumbbell.

If, for example, the value of $r_2$ were selected so that $m_2 r_2 \neq m_1 r_1$, the vehicle would not rotate about point O, but would in fact rotate about the actual center of mass of the system, in accordance with the laws of mechanics. Assuming constant $\bar{w}$, this shift in the axis of rotation would result in a change in the gravity level at Sphere 1 and at every other point in the vehicle.

Any change in mass distribution along the rod of the dumbbell could cause a similar effect. Thus, in an actual vehicle in which mass distribution could be expected to change frequently due to movement of personnel, flow of fluid mass, motion of the moving parts of machinery, addition or loss of mass, etc., the continual redistribution of mass which would take place would cause the continual shift of the center of mass (c.m.) of the vehicle with an accompanying variation in "g"-level at every point in the vehicle. While minor shifts in mass could be tolerated, any major shifts in mass, if uncompensated, could result in an unstable rotation which would make the vehicle unsatisfactory from both human-factors and engineering viewpoints.

It is clear that for stable rotation, provision must be made to

maintain a constant c.m. and a constant $\bar{w}$ regardless of transient changes in mass distribution within the vehicle. Two provisions must be made in the design of the vehicle to provide rotational stability. Provision must first be made for including an automatic stabilizing system in the vehicle. Provision for inherent vehicle stability must also be made, not only to minimize the performance requirements of the automatic system, but also, as mentioned by Schnitzer (Ref 34:3), to provide backup stability in the event of failure of the automatic system.

The function of the primary stabilization system is to maintain constant $\bar{w}$ and a constant vehicle c.m. through compensatory shift of mass and/or application of corrective torques, the entire process to be performed automatically.

Inherent stability of a rigid vehicle can be provided by rotating the vehicle about either the major or minor axis of inertia, any other axis being inherently unstable (Ref 42:293). For a perfectly rigid vehicle, choice of major or minor axis is arbitrary since rotation will be stable about either axis. But for a non-rigid vehicle or a vehicle in which internal damping due to mass shifts, sloshing fluids, etc., will result in dissipation of rotational energy, the minor axis of inertia is an unstable axis (Ref 27:49). Since some dissipation of rotational energy due to mass shifts and flexure of the structural members is probable in the vehicle under consideration, it appears that the logical choice is to rotate the vehicle about its major axis of inertia to maximize rotational stability.

The problems involved in vehicle stability are extremely complex and are among the most difficult which will be encountered in

engineering design. Since a detailed analysis of them is not relevant to the subject under consideration, they may be dropped from further consideration.*

Rotational Stability Design Principles. For the purpose of se-lection of an optimum configuration, it is sufficient to note that the vehicle configuration should be one in which the intended axis of rotation coincides with the major axis of inertia of the vehicle.

A particular design conflict which involves stability versus structural economy should also be noted. It has previously been indi-cated that placement of mass at the axis of rotation involves minimum structural penalty. In view of stability requirements, however, there is a limit to the amount of mass which may be strung out along the axis of rotation, the limit being prescribed by the requirement that the major axis of inertia of the vehicle be coincident with the vehicle spin axis. This requirement must be met, at the expense of structural economy if necessary.

## Operational Factors

Operational factors which are intimately related to engineering factors and overall vehicle design are those involving mission require-ments, the resupply operation, maintenance, and emergency escape.

Mission Requirements. For the performance of some of the many operational activities in which the orbiting space station will be engaged (Refs 3:183; 1:124), such as earth surface and celestial observation, there will undoubtedly be a requirement for an inertially-stable platform. While it would be convenient to locate this platform

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*
Treatment of some of the problems of stability can be found in Refs 23:53; 28:114; and 29.

at the living-working compartment, the advantages to be gained in structural economy and simplicity by locating the platform on a non-rotating hub at the axis of rotation would probably outweigh any disadvantages involved in the remote readout of data and operation of platform equipment such as telescopes, cameras, radar, infra-red scanners etc. The advantages to be accrued from a stable platform located at the spin axis of the vehicle appear to make it mandatory that the vehicle design include a non-rotating compartment at the axis.

If zero-gravity experiments are to be conducted, they will of necessity have to be conducted at the axis of rotation. The zero-"g" experimental compartment can be included in the hub along with the stable platform.

The Resupply Operation. Analysis of the problems involved in rendezvous and docking of the resupply vehicle with the orbiting satellite favor a decision for the docking to take place at the axis of rotation of the vehicle rather than at the living-working compartment. The reasons for this choice are:

(1) The use of a docking facility at the spin axis simplifies the terminal guidance problem for the resupply vehicle.

(2) Docking facility mass can be located at the spin axis.

(3) Vehicle stability will be relatively undisturbed during the resupply operation.

The disadvantages involved in docking at the living-working compartment can be minimized by cessation of vehicle rotation during the resupply operation, but the addition of docking facility mass to the compartment would sacrifice structural economy. In addition, rerotation of the vehicle could not occur if departure of the resupply

vehicle were delayed without seriously overtaxing the automatic st.-
bilizing system of the vehicle. Thus, it may be concluded that th.
resupply vehicle should be docked at the hub of the vehicle.

Consideration must be given to the advisability of stopping
vehicle rotation during the resupply operation, even for docking at
the axis of rotation. Some of the advantages to be gained are:

(1) A non-rotating docking hub would not be necessary.

(2) The complex facility necessary for transfer of personnel
and supplies from the non-rotating hub to rotating compartment could
also be eliminated. The mechanism involved in such a facility has
been discussed by Ross (Ref 33:13) and Ley (Ref 28:114).

(3) Radial traffic of personnel, which would be maximized
during the resupply operation, would occur under weightless condition
rather than under the stressful conditions characterized by the
combination of Coriolis and centrifugal forces which accompany
radial motion during rotation.

The disadvantages incurred are:

(1) The living-working compartment would have to be design.
for operation under both weightless and artificial gravity environment...
although this requirement would probably have to be met anyway, for
initial use of the compartment as a non-rotating vehicle during
in-orbit construction of the finished space station.

(2) All crew members would be subject to weightlessness dur..
the resupply operation. This is not an appreciable disadvantage.
It is fairly certain that weightlessness over a period of a few hours
has no detrimental effects. Further, the change would probably be a
welcome diversion from the monotonous routine of normal activity.

Finally, the weightlessness would not be as stressful as radial motion during rotation would be.

(3) Crew members would probably experience illusions during the rotational accelerations involved in slowdown or speedup of the vehicle. The occurrence of illusions could be minimized, however, through use of low acceleration rates and by motionless positioning of crew members during these intervals.

(4) Energy would have to be expended each time rotation were stopped or started. The mass of the propellants required to produce the necessary torque would involve considerable mass (Ref 23:53) and over a long period of time the mass penalty would more than overcome the initial mass savings realized in eliminating the requirement for a completely non-rotating hub and the transfer mechanism.

Although it would be advantageous from a human-factors viewpoint to stop vehicle rotation during the resupply operation, the long term mass penalty involved would be prohibitive. It should be noted that if some practical system could be devised which would minimize the energy (mass) penalty involved in starting and stopping rotation, the decision to stop vehicle rotation for resupply and other operations would be preferable. Two possibilities for such a system might be feasible. Both involve the use of a counter-rotating flywheel, i.e.,

(1) Transfer of angular momentum of the rotating vehicle to the non-rotating flywheel during deceleration of the vehicle, with reverse transfer of the momentum back to the vehicle during acceleration to normal rotating speed. The energy lost in the process to be supplied by spin rockets, and/or

(2) Use of electrical energy from the nuclear power source to rotate the vehicle in one direction against the inertia of the flywheel in the other, both for starting and stopping vehicle rotation.

The feasibility of both these devices would be enhanced if flywheel mass could be made to consist of useful mass.

Until an efficient system for either storing and recovering energy, or for producing it inexpensively, is proved to be feasible, the evidence appears to indicate conclusively that the vehicle should rotate continuously with provision made for a completely non-rotating hub and the accompanying transfer mechanism. The non-rotating hub might thus consist of a large zero-"g" experimental compartment, the docking facility, the transfer mechanism, and the stable platform, all perhaps enclosed in a shirt-sleeve environment, although this latter provision might be considered an unnecessary luxury.

Maintenance. Maintenance of the vehicle and its components at locations other than the non-rotating hub and in the living-working compartment would probably best be performed at times when the vehicle were not rotating, to preclude the occurrence of canal sickness to which crew members would be susceptible while moving and working at external points on the rotating vehicle structure. Since economy forces the choice of a continuously rotating vehicle, however, external vehicle maintenance will have to be performed while the vehicle is rotating.

The adverse human-factors effects can be minimized through

(1) Reliability and redundancy of components, particularly those remotely located.

(2) Provision made for low-velocity transport mechanisms

along the connecting structure which would permit passive transport of crew members as well as transport of equipment.

(3) Arrangement of external vehicle components so that maintenance can be performed from fixed-station positions with the preferred body orientation, i.e., crew member lateral axis parallel to vehicle spin axis.

Emergency Crew Escape. While provision cannot be made to insure crew protection against catastrophe, a requirement for emergency escape from the vehicle will exist. Escape capability can most economically be provided through the use of one-way re-entry capsules or gliders anchored to the satellite vehicle. Structural economy can be observed by locating these "lifeboats", as they are referred to by Ehricke (Ref 10:22), remotely from the living-working compartment, under the assumption that sufficient time will be available in any probable emergency to permit the crew to reach the lifeboats and escape. The lifeboats could thus be located at the spin axis or to provide countermass or stability to the vehicle. For the latter two choices,

(1) The lifeboats would be considered more-or-less as permanent ballast, to be used only for abandonment of the vehicle;

(2) In the event the space station were to be abandoned, launching of the lifeboats would be facilitated by stopping vehicle rotation prior to launch. No additional mass penalty would be involved in stopping vehicle rotation since the propellant would be on board the vehicle at all times anyway, to permit one or two stop-start-rotation cycles if necessary in the course of normal operation.

## Summary of Engineering and Operational Design Principles

The design principles which have been derived from an investigation
of engineering and operational factors may be briefly summarized as
follows:

(1) The living-working compartment should be placed at the
outermost radius of the vehicle.

(2) The compartment should consist of minimum mass. Only
those items essential to mission accomplishment (display and control
equipment) and to crew safety and comfort should be located in the
living-working compartment.

(3) All remaining components with the exception of the com-
ponents discussed below, should be used as countermass to minimize
countermass radius, or to satisfy stability requirements.

(4) The stable platform, the zero-gravity experimental
compartment, and the docking facility for the resupply vehicle should
all be located at the axis of rotation in a non-rotating compartment.

(5) The vehicle should rotate continuously, with provision
made for transfer between the rotating structure and the non-rotating
hub through use of a transfer mechanism.

(a) Maximum remote operation capability should be built
into the vehicle to minimize human traffic in the radial direction and
in the non-rotating compartment.

(b) Low-velocity transport mechanisms should be provided
for passive radial transport of personnel and for transport of
supplies and equipment.

(c) Maintenance duty stations on the external vehicle
structure should be designed to permit preferred body orientation of

crew members while performing maintenance.

(6) The vehicle must have rotational stability.

(a) An automatic stabilization system must be provided.

(b) To provide inherent stability, the major axis of inertia of the vehicle should coincide with the intended axis of rotation.

(7) Emergency one-way escape vehicles should be located at the axis of rotation or positioned to satisfy countermass or stability requirements.

The principles listed above are not all to be taken as rigid, inflexible rules but as basic parameters which can be used in making any tradeoffs necessary to achieve optimum vehicle design.

These principles and those developed in the previous chapter provide sufiicient criteria to permit the selection of an optimum configuration for the vehicle. The investigation will be concluded in the next chapter with the selection of the optimum configuration, an illustration of the application of the derived parameters in the conceptual design of a proposed vehicle, and some comments on minimal-capability design and current design proposals.

V. The Optimum Vehicle Configuration

With the human, engineering, and operational factors as parameters against which various possible vehicle configurations may be compared, it is possible to select a configuration which is optimum from an artificial gravity viewpoint. With the investigation thus essentially completed, the integrated application of the principles derived from the investigation may be illustrated in the conceptual design of an actual vehicle. Some brief comments on minimal capability design and some current design proposals will conclude the study.

Analysis of Various Possible Vehicle Configurations

While many vehicle configurations are possible, there are essentially only three basic configurations, all stemming from the prototype idealized dumbbell. The first is the dumbbell itself, with either a rigid or flexible shaft. The second is the torus, which is a figure of revolution obtained by rotating a symmetrical dumbbell about its major axis of inertia. The third may be described as an axially-expanded dumbbell. This configuration is obtained by using parallel cylinders rather than spheres and by using one or more connecting shafts.

The Dumbbell with Flexible Shaft. This configuration, characterized by a living-working compartment and a useful or deadweight countermass, connected by a long, steel cable, is the only one which approaches practicality for vehicles of extremely large radius (Figure 13, on the following page). The design of such a vehicle, using a tapered cable-

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length of about 5 miles, is dis-
cussed in detail by Oberth
(Ref 30). The use of flexible
cable, which provides the highest
possible strength-to-mass ratio,
is feasible because under a con-
stant rate of rotation the only
force acting on the connecting
structure, i.e., the cable, is
tensile force. The advantage to
be gained through the use of this



FIGURE 15. ILLUSTRATION OF USE OF DUMBBELL-WITH-FLEXIBLE-SHAFT CONFIGURATION TO CREATE ARTIFICIAL GRAVITY IN SPACE VEHICLE.
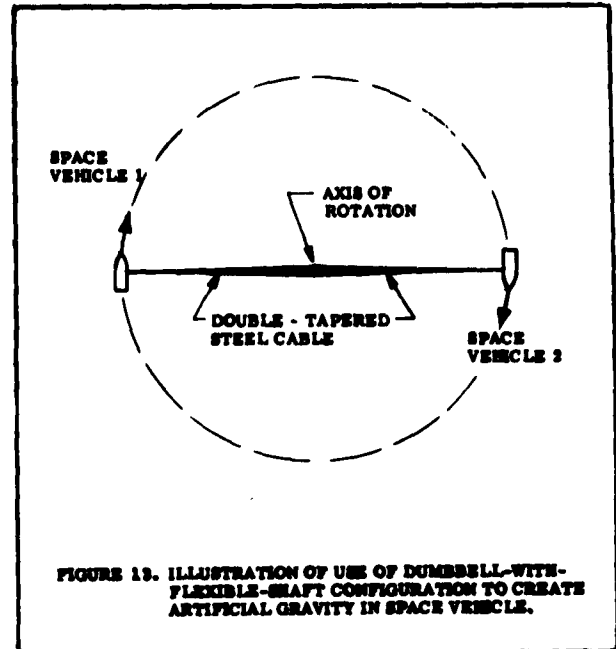
configuration is the extremely low value of angular velocity which can be used
to provide artificial gravity. From a human-factors viewpoint this
advantage is important, since $\bar{w}$ is intimately connected with the source
of most of the human-factors difficulties, i.e., Coriolis forces. In
fact, if human factors alone were to be considered, this configuration
would be ideal. For the vehicle under consideration in this study,
however, the design has too many disadvantages to be of value, i.e.,

(1) For extremely large $\bar{r}$, the countermass would be too remote
to be useful mass, unless it were a second, completely independent
vehicle with its own crew.

(2) For cable lengths greater than about $5\frac{1}{2}$ miles, tidal forces
would become unpleasant (Ref 30:85).

(3) Because flexible cable cannot support a bending moment,
acceleration of the vehicle (or vehicles) to rotational speed or
deceleration to zero angular velocity would be a difficult maneuver.

(4) On cessation of rotation, the relaxation of the taut cable

would tend to pull the living-working compartment and the countermass toward each other with erratic motion and possibility of collision. The danger would be heightened if the countermass on a small-radius vehicle were to consist of a nuclear auxiliary power source. In this situation, as pointed out by Ehricke (Ref 11:313), unless the reactor were completely encased in shielding (at large expense in mass), there would be a radiation danger to the crew members.

(5) All facilities would have to be placed in the living-working compartment at the expense of structural economy, and of stability during the resupply operation.

In general it may be concluded that a vehicle of this configuration would have usefulness only as a minimal-capability vehicle, for which empty tankage or other booster debris on a relatively short length of cable, or mere cable-length alone, could serve as countermass to a small, manned compartment designed for a short-duration mission. The configuration does not appear to be a favorable one for a large, permanent space-station.

The Dumbbell with Rigid Shaft. This configuration has an advantage over that discussed above in that it is able to withstand bending moments and any relaxation-compression which might accompany cessation of rotation. Thus, use of a nuclear reactor as countermass would require only uni-directional, shadow-type shielding with corresponding savings in overall mass. However, the radius used for the rigid dumbbell would be restricted to much shorter lengths because a long connecting structure would have to be massive to resist bending moments. Shorter values of radius would naturally require use of larger values of $\bar{w}$ with an accompanying increase in Coriolis forces.

Rocket boosters presently in use are particularly adaptable to this configuration. Because of its elongated cylindrical shape, the booster can serve as the rigid connecting structure, with a living-working compartment at one end and, as in a proposal by Ehricke (Ref 10), a nuclear power source as countermass at the other, as shown in Figure 14, on the following page.

The primary disadvantage connected with use of this configuration is the limitation in the lateral dimensions of the living-working compartment. This limitation can be minimized through the use of several "floors", each at a different radius with a different "g"-level. Radial expansion of the living-working compartment is more or less dictated by necessity when the booster itself is used as the dumbbell structure.

Because of the disadvantages which result from a human-factors viewpoint, i.e., the existence of several different "g"-levels and the radial traffic which becomes necessary in a radially-oriented compartment, the configuration is not considered to be optimum.

The Torus. The limitation in the lateral dimensions of the living-working compartment of the dumbbell can be alleviated by extending the compartment in the tangential or axial directions. The torus configuration is obtained by extension of the compartment in the tangential direction, i.e., the torus is a body of revolution formed by a rotation of a symmetrical dumbbell about its major axis of inertia. The torus configuration has been popularized as a "Space Wheel" because of its obvious resemblance to an inflated inner-tube with radial spokes leading to a central hub, as is reflected in Figure 15, on page 61. The configuration was made famous by Von Braun (Ref 39) with his celebrated proposal in

Figure 1. Illustration of ... of J..SELL-INs...RAFT SEPARATOR in 261 A TWO-STAGE MISSILE (Ref 10). (Reproduced with permission of R. Ehricke and the author.)

1952, although essentially the same configuration was proposed earlier by Ross-Smith (Ref 33). It has also been favored by Ley (Ref 28), Romick (Ref 2), and more recently by Schnitzer (Ref 34), among others.

Schnitzer (Ref 34:5), in his proposal for a minimal-capability experimental torus, has listed some advantages of the torus configuration as follows:



FIGURE 14. ILLUSTRATION OF USE OF TORUS CONFIGURATION IN DESIGN PROPOSAL BY VON BRAUN (REF 39)

(1) The configuration is compatible with a large parabolic solar collector which can be placed in the center of the wheel.

(2) The spinning torus can easily be stabilized since the torus is rotated about its major axis of inertia.

(3) There is an equal gravity level everywhere along the outer wall, i.e., the "floor", of the torus.

To these advantages of the torus configuration, of which the last is the most important from a human-factors viewpoint, may be added the ease with which the "inner-tube" configuration lends itself to the use of an inflatable material as the primary vehicle structure.

There are several disadvantages which accompany use of this configuration. They stem primarily from the fact that the plane of the torus lies in the plane of rotation, i.e., the plane in which motion produces maximum Coriolis forces, as was determined in Chapter II,
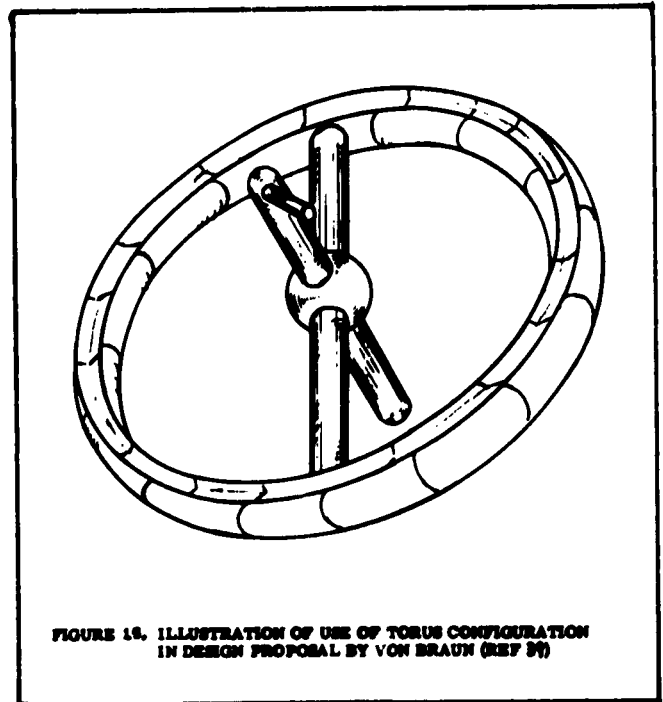
page 12. The disadvantages are:

(1) The major axis of traffic is tangential. Therefore, crew members would be subject to continual variations in gravity-level while moving back and forth.

(2) Orientation of bunks and control consoles to minimize the incidence of canal sickness would require that they be placed perpendicular to the "aisle" rather than along it. This arrangement would probably result in inefficient use of space.

(3) Visual conflict would be prevalent unless special precautions were taken in interior design.

(a) The change in apparent vertical from one point to another further down the aisle would be obvious and disconcerting.

(b) The curvature of the floor in the direction of the aisle would be apparent. The crew member would always be in a "valley."

(c) It would always appear to the crew member walking along the aisle that he were walking "uphill." At the same time, while walking against the spin, he would feel "lighter," i.e., he would feel as though he were walking "downhill." It may be expected that the resulting conflict would be particularly stressful.

These phenomena would be emphasized in small-radius vehicles and less apparent for vehicles of large radius. While compartmentalization of the torus would help to minimize some of the visual conflict, it could not be completely eliminated.

(4) The torus cannot very well be optimized for size. Once a radius for the floor of the living-working compartment is selected from the design envelope, the size of the torus is automatically established with a circumference of $2\pi r$, regardless of whether or

not the resulting space provided is optimim. The location of most of the vehicle components at the radius of the torus compartment to make maximum utilization of space within the torus would involve unnecessary structural penalties.

This disadvantage could be minimized by using an interrupted torus, in which only segments of the torus would be used, with each segment connected to the hub by one or more spokes, but this modification would result in extensive radial traffic if more than one of the segments were to be occupied. If not, the configuration would essentially degenerate into a dumbbell with all of the above disadvantages still present.

It may be concluded that an expansion of the living-working compartment of the dumbbell in the tangential direction would result in a magnification of the inadequacies inherent in the artificial gravity environment, and in inefficient economy of structure. Because the torus is admirably suited to the use of an inflatable material as its basic structure, the configuration has some value as a minimal-capability, experimental vehicle. But its inherent disadvantages bar its selection as an optimimum configuration.

The Axially-Expanded Dumbbell. The alternate direction in which the living-working compartment of the dumbbell may be extended is the axial direction. This configuration is obtained by merely expanding the dumbbell along the spin axis. The most prominent example of the use of this configuration is in a proposal by Kramer and Byers (Ref 23:37), although the basic configuration is evident in an earlier proposal by Ehricke (Ref 12). The Kramer and Byers vehicle, shown in Figure 16, on the following page, provides for two symmetrically-opposed
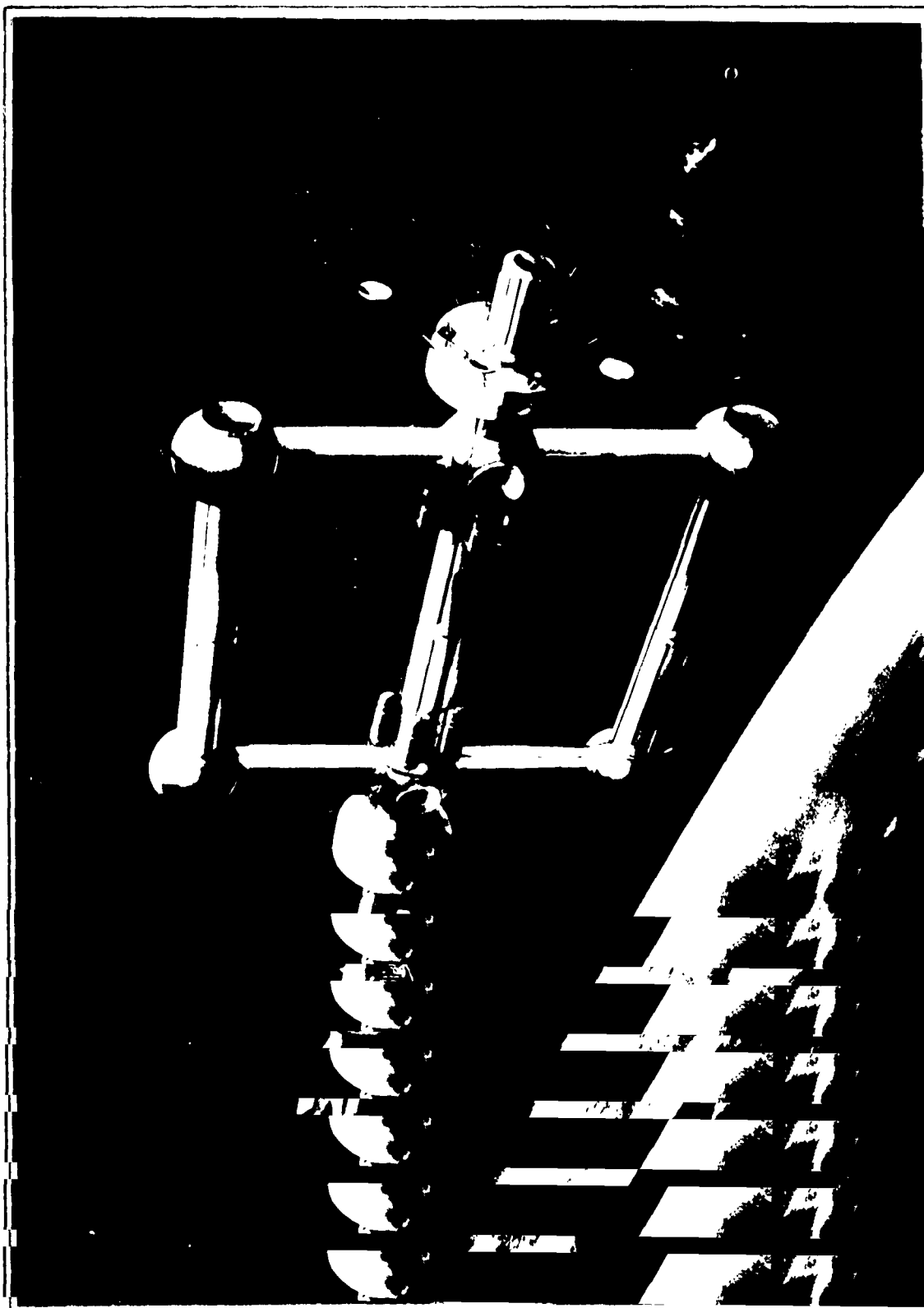
living-working compartments, and two radial shafts (plus a third com-
partment along the spin axis).

The axially-expanded dumbbell configuration has the inherent
advantages which accrue as a natural consequence of the orientation
of the major dimension of the living-working compartment parallel to
the axis of rotation.  The design minimizes the detrimental effects
of the artificial gravity environment caused by Coriolis forces.
The advantages are:

(1) The major axis of traffic is axial.  Therefore crew
members would experience a constant gravity-level while moving back
and forth along the living-working compartment.  Increase and decrease
in "g"-level accompanying tangential motion would be minimized because
such movement would occur across the relatively narrow dimension of the
compartment.  Such movement would probably occur at velocities less
than the assumed 4 ft/sec indoor walking velocity; hence the effect
would be further minimized if not practically eliminated.

(2) Orientation of crew bunks and control consoles parallel
to the aisle and against the walls would be ideally compatible with
the axial orientation of the aisle.

(3) Visual conflict would be minimized.

(a) There would be no change in apparent vertical anywhere
along the center of the aisle.  Change in apparent vertical across the
aisle would be minimized due to the narrow dimension in the tangential
direction, and for a large-radius vehicle the change would probably
be imperceptible.  Assuming a 10 ft floor-width across the aisle, the
total change in the angle of the vertical across the compartment would
be $10^{\circ}$ for a minimum permissible vehicle radius of 60 ft, and less than

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$4^{\circ}$ for a design radius of 180 ft.

(b) The floor would be perfectly flat along the length of the compartment. The crew member walking back and forth along the aisle would experience a constant "g"-level compatible with what his eyes would see as a flat, level surface. To compensate for the slight variation in vertical across the compartment, a slight lateral curvature could be built in for small-radius vehicles. For large-radius vehicles the floor could be made perfectly flat.

(4) The axially-expanded dumbbell can more easily be optimized with respect to size. The relationship between the radius selected for the vehicle and the length of the living-working compartment would not be fixed, as it is for the torus. The only limit on compartment length would be that imposed by the requirement for inherent vehicle stability.

(5) The cylindrical shape of the living-working compartment would simplify the boost problem, since the shape would be compatible with the cylindrical shape of the booster.

The disadvantages are:

(1) The configuration has the inherent disadvantages which result from the use of a second living-working compartment as counter-mass to the first.

(a) Essentially two separate closed ecological systems or one large, complex one would be required.

(b) Radial traffic would be extensive.

(2) Design for inherent stability would be more critical for this configuration than it would be for the torus. The configuration would have less inherent stability because the stretching out of

dumbbell mass in the axial direction would tend to increase the moment of inertia about an axis perpendicular to the axis of rotation.

In summary, of all the configurations considered, the axially-expanded dumbbell is unique in that it minimizes the undesirable effects of the artificial gravity environment. Its disadvantages can be eliminated or compensated for through slight modification and proper design.

### The Optimum Configuration

The optimum configuration is a Modified Axially-Expanded Dumbbell in which only one of the two cylinders is used as a living-working compartment. Useful countermass, consisting of vehicle components, is used in place of the second compartment. This modification results in the elimination of the requirement for a complex closed ecological system, and min-mizes radial traffic and its detrimental effects, thus making the configuration optimum from a human-factors versus engineering viewpoint, without sacrificing operational suitability.

The optimum configuration is reflected in the vehicle illustrated in Figure 17, on the following page. A description of the vehicle, referred to as the Pseudo-Geogravitational Vehicle because it provides an artificial gravity environment which approximates that on earth, will serve to illustrate the application of the design principles derived in this study.

### The Pseudo-Geogravitational Vehicle (P.G.V.)

The selected values for the rotational variables $\bar{w}$ and $\bar{r}$ are indicated on the human-factors design envelope of Figure 18, page 75, by the point labeled P.G.V. It is seen that this operating point

NUCLEAR AUX. POWER SOURCE

SHIELDING

USEFUL COUNTERMASS
(Massive Components - Batteries
Machinery, Stores, etc.)

MISSION EQUIPMENT HUB
(Stable Platform, Telescopes,
Infra-Red and Radar
Equipment, etc.)

DOCK FOR ESCAPE VEHICLE
(Permanent Ballast)

DOCKING HUB

TRANSFER MECHANISM

AXIS OF
ROTATION

180'

LIVING-WORKING
COMPARTMENT
(Closed Ecological System)

NOTE: Entire Hub Non-Rotational

FIGURE 17. ILLUSTRATION OF USE OF THE MODIFIED AXIALLY-EXPANDED
DUMBBELL CONFIGURATION IN THE CONCEPTUAL DESIGN OF A
MANNED ORBITAL SATELLITE VEHICLE

lies at the upper border of the envelope at the minimum possible radius which permits achievement of the upper "g"-limit. The designated operating point is significant because:

(1) Of all the operating points which lie within the design envelope, it is an optimum operating point which reflects considerations of practicality at the same time that it provides a nearly earthlike artificial gravity environment. As such, it represents the upper limit of difficulty of the engineering design problems connected with artificial gravity in manned orbital satellite vehicles.

(2) It establishes a practical upper limit on $\bar{r}$, since the range of $\bar{r}$ values between 60 ft and 180 ft permit the selection of the entire range of permissible "g"-values. The upper limit, indicated on the design envelope by the vertical dashed line, serves to narrow the region of interest for future design. It may therefore be concluded that the design of future vehicles should be based on operating points which lie within the shaded area.

The P.G.V. Artificial Gravity Environment. The selected operating point corresponds to a value of 0.4 rad/sec for $\bar{w}$, and a value of 180 ft for $\bar{r}$. Thus the floor of the living-working compartment of the illustrated vehicle is located 180 ft from the axis of rotation. The corresponding "g"-level is seen from the graph to be about 0.9 g. This "g"-level will be experienced by crew members both when stationary and when walking along the length of the compartment. The gravity gradient as a percentage of floor-level "g" is a negligible 3.3%. The percent change in gravity experienced by crew members walking across the aisle of the compartment, which figure may be obtained directly from the graph

of Figure 9, page 18, will be about 11%. This figure is conservative since it is based on normal walking velocity. Movement across the narrow dimension of the compartment will probably be at lower-than-normal walking velocities. The possibility that some canal sickness symptoms will be experienced cannot be eliminated, but any inadequacy of the environment in this respect can be minimized through careful crew selection, crew training, and proper design of the vehicle, as discussed below.

The Living-Working Compartment. The single living-working compartment at the lower end of the figure consists of a closed ecological system which provides for a shirt-sleeve environment. All human activity outside the compartment is conducted essentially in the space environment. The compartment itself contains only those minimum components required for display and control, and life support. One or more air locks is provided in the roof of the compartment for entry and egress. The compartment is designed to operate under zero gravity as a self-sustained unit during in-orbit construction of the vehicle.

Control consoles are located against the walls of the compartment and are vertically oriented. Bunks in the off-duty section of the compartment are placed on both sides of the aisle and are axially oriented. (The orientation of both these components is as illustrated in Figure 11, page 30.) The floor is perfectly flat. The interior decoration emphasizes spaciousness and the normal vertical-horizontal orientation which exists in earth-bound facilities. With the exception of viewing ports located in the roof, the compartment is windowless.

The more massive components of the compartment are located in

the roof to minimize the requirement for countermass. Provision for housing these components is indicated in the illustration by the boxlike structure which caps the compartment.

Engineering Design Features. The living-working compartment is counterbalanced by vehicle components and a nuclear auxiliary power source. It should be noted that the figure merely illustrates the relative positioning of the vehicle components. No attempt has , been made to indicate the relative size or the radius to each of the components, nor should any conclusions be drawn concerning these parameters from the scale of the drawing.

Inherent stability about the designated spin axis is achieved primarily through counterbalancing two permanent-ballast, one-way escape vehicles in the plane of rotation, as shown. Axial distribution of mass is minimized by concentrating the more massive components of the living-working compartment toward the center of the compartment and by locating the least massive items at the extremities.

The non-rotating hub consists essentially of a hollow cylindrically, shaped compartment located at the vehicle spin axis, with the stable platform containing mission equipment (telescopes, cameras, etc.) at one end and the docking hub at the other. Ample space is provided for zero-"g" experiments.

Vehicle Operation. Since mission equipment located in the non-rotating hub is remotely monitored and operated, crew members will for the most part remain in the shirt-sleeve environment of the living-working compartment during normal operation. The normal activities which require crew members to leave the shirt-sleeve environment are few, infrequent, and for the most part involve short-time exposure to

the sub-gravity space environment. The activities referred to are:

(1) Transfer of personnel, supplies, and equipment during the resupply operation.

(2) Performance of external vehicle maintenance.

(3) Conduct of those zero-"g" experiments which require participation or presence of crew members in the non-rotating compartment.

## Minimal-Capability Design

The operating point for the minimal-capability vehicle should obviously be chosen at the smallest permissible value of radius within the design envelope, i.e., 60 ft. The problems involved in the engineering design of the 60 ft-radius vehicle will be appreciably simplified, which should facilitate the realization of an experimental vehicle in the near future using present state-of-the-art components. Such a vehicle would be an invaluable forerunner to the fully operational PGV.

## Current Design Proposals

The relationship to the design envelope of the operating points for some well known design proposals are indicated in Figure 18, page 75.

Those which may be considered to be minimal-capability vehicles are the Schnitzer torus (Ref 34), which is an experimental vehicle of 20 ft radius designed to provide 0.0 - 0.5 g through variation of $\bar{w}$, and the Ehricke 4-man rigid dumbbell (Ref 10:22), which is to operate at a fixed value of $\bar{w}$ but with several floor-levels, each located at different radius with a different "g"-level.

Those which are advanced-capability vehicles are the Von Braun torus (Ref 39), which is to operate at constant $\bar{w}$ but with different

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"g"-levels for each of three radially-separated floors, the Ehricke 8-man rigid dumbbell (Ref 10:23), which is an advanced version of the 4-man vehicle, and the Kramer and Byers axially-expanded dumbbell (Ref 23), which provides for a one "g" environment at the floor-level of each of the two outer compartments.

VI.  Summary, Conclusions, and Recommendations

Summary

The objective of the investigation has been the synthesis of design criteria which optimize manned orbital satellite vehicle design with respect to artificial gravity.  Human factors have been given paramount consideration.

The first step in the investigation has involved an analysis of the artificial gravity environment and its peculiarities in terms of the rotational parameters $\bar{w}$ and $\bar{r}$.  An analysis of human factors based in part on experimental evidence and in part on assumptions has led to the establishment of a human-factors design envelope and some human-factors design principles.  An analysis of engineering and operational factors has provided design criteria which, in conjuntion with the basic human-factors design criteria, has led to the selection of an optimum configuration for the vehicle.

Application of the derived criteria has been illustrated in the conceptual design of a vehicle rotated to provide a nearly-earthlike artificial gravity environment.

Conclusions

The Human-Factors Design Envelope.  The design envelope is pre-scribed in Figure 18, on the following page.  The limits are prescribed as follows:

(1) The Upper Limit on Vehicle Angular Velocity ($\bar{w}$) - established at 0.4 rad/sec, to minimize the occurrence of "canal sickness" (pp. 22-27).

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FIGURE 16. HUMAN-FACTORS DESIGN ENVELOPE SUPERIMPOSED ON PLOT OF ANGULAR VELOCITY ($\bar{\omega}$) VERSUS RADIUS OF ROTATION ($\bar{r}$) TO ACHIEVE VARIOUS LEVELS OF ARTIFICIAL GRAVITY. OPERATING POINTS FOR PSEUDO-GEOGRAVITATIONAL VEHICLE (P. G. V.) AND OTHER CURRENT DESIGN PROPOSALS ARE INDICATED
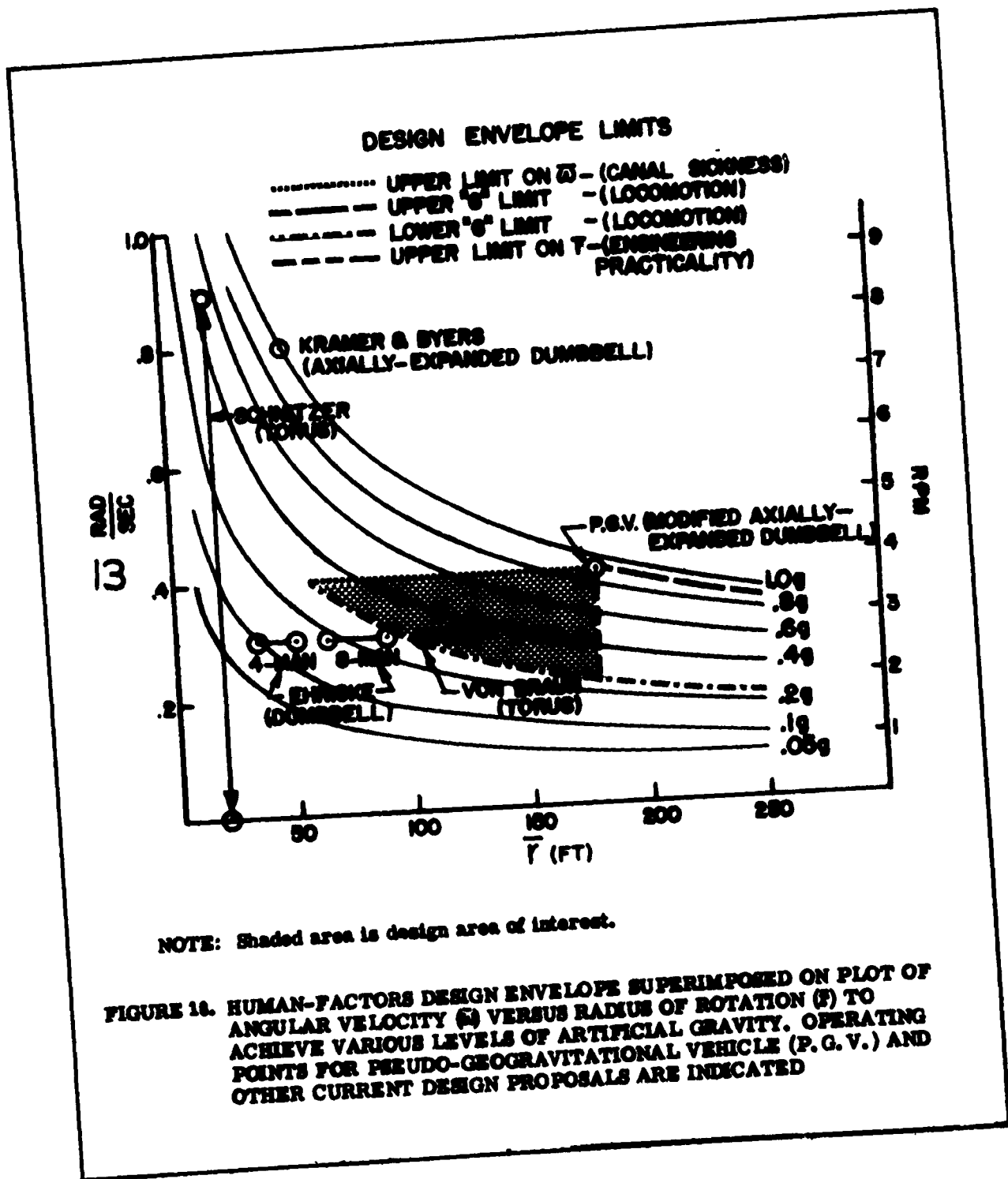
(2) The Upper Limit on Artificial Gravity - established as a one "g" maximum, modified to compensate for Coriolis effects for tangential walking in the direction of spin (pp. 30-33).

(3) The Lower Limit on Artificial Gravity - established as 0.2 g minimum on the assumption that the lowest value of artificial gravity to be permitted is that minimum value (0.2 g) at which man can walk unaided, the minimum limit modified to compensate for Coriolis effects for tangential walking against the spin (pp. 33-34).

(4) The Practical Upper Limit on Vehicle Radius ($\bar{r}$) - established at 180 ft based on engineering considerations (pp. 42-43), 67-69).

Human-Factors Design Principles.

(1) Radial traffic should be kept to a minimum (pp. 15-16, 35-36).

(2) Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is non-rotating (pp. 8-10, 15-16, 35-36).

(3) The living-working compartment should be located as far as possible from the spin axis (pp. 35-36, 42-43).

(4) The compartment should be oriented so that its major dimension is parallel to the vehicle spin axis (pp. 14, 37, 68).

(5) Crew duty-station positions should be oriented to provide the preferred orientation of the crew member's lateral axis (pp. 27-30).

(6) Sleeping bunks should be oriented with their long axis parallel to the vehicle spin axis (pp. 27-30).

(7) The presence of confusing visual stimuli should be minimized (pp. 22-23, 38-39).

Engineering and Operational Design Principles.

(1) The living working compartment should be placed at the outermost radius of the vehicle (pp. 42-46, 68).

(2) The compartment should consist of minimum mass, i.e., those items essential to mission accomplishment and to crew safety and comfort (pp. 42-44).

(3) All remaining components, with the exception of those listed below, should be used as countermass or to meet stability requirements (pp. 44-48).

(4) The stable platform, the zero-gravity experimental compartment and the docking facility for the supply vehicle should all be located at the axis of rotation in a non-rotating compartment (pp. 48-52, 68).

(5) The vehicle should rotate continuously, with provision made for transfer from the rotating structure to the non-rotating hub through use of a transfer mechanism (pp. 49-53, 68).

(6) The vehicle must have rotational stability (pp. 46-48).

(7) Emergency one-way escape vehicles should be located at the axis of rotation or positioned to meet countermass or stability requirements (pp. 53, 68, 71).

The Optimum Vehicle Configuration. The optimum configuration is a Modified Axially-Expanded Dumbbell (pp. 63-67). Its features are illustrated in the conceptual configuration shown in Figure 17, page 68, and described on pp. 67-72.


Recommendations for Future Research

Human Factors. More conclusive and precise experimental data must

be obtained on human-factors stress limits, particularly those pertaining to canal sickness and the lower limit on artificial gravity.

The upper limit on vehicle angular velocity established in this investigation represents a compromise between practicality and inconclusive experimental evidence. It should be possible to define this upper limit with a greater degree of precision through further experimentation in rotating-room environments involving a large number of test subjects.

The validity of the assumption that the lowest value of subgravity at which man can walk unaided is the minimum necessary to satisfy the psychophysiological needs of man cannot be established until long-period human-orbit times can be achieved. But a more precise value of the minimum "g"-level for unaided walking can be established, and will be forthcoming in the near future as a result of experiments to be conducted by the Aerospace Medical Laboratory personnel at Wright-Patterson Air Force Base.

Since the upper limit on $\bar{w}$ and the lower "g"-limit are critical parameters of the human-factors design envelope, a refinement of these limits based on further experiments, which are within present capability, will enhance the usefulness of the design envelope established herein.

Engineering Design. Other than to consider those factors which are relevant to the selection of an optimum configuration and to insure practicality, the subject of engineering design has been subordinated in this investigation. There are many engineering problems which will bear further investigation in the light of the conclusions reached in this study. Some of the problem areas which merit detailed investigation

are those involving distribution of vehicle mass, rotational stability
and control, living-working compartment design, shielding of vehicle
components and crew members from the radiation environment of space
and of the nuclear reactor, etc.

Selection and Training of Crew Members. Because canal sickness
is the most critical of human factors connected with the artificial
gravity environment, screening of astronaut candidates should include
an evaluation of susceptibility to canal sickness. Effort should
be devoted to the design of the test device and the test procedure.

Astronauts in training for duty in the artificial gravity
environment should be exposed to the peculiarities of a rotating-
vehicle environment to the extent that earth-bound facilities will
permit. Effort should be devoted to development of a training facility
which will most nearly simulate the rotating-vehicle environment.

Thesis Research Topics. The field encompassed by this investi-
gation has been relatively broad. There are thus any number of topics
to which a thesis effort can be devoted. Some particular topics
which are sufficiently well defined to permit treatment as individual
research efforts are:

(1) Experimental Theses

(a) Establishment of the precise lower limit of sub-
gravity at which man can walk unaided. The experiment to be performed
under the sponsorship of the Aerospace Medical Laboratory, Wright-
Patterson Air Force Base (pp. 33-34).

(b) Establishment of a more precise upper limit on $\bar{w}$
based on susceptibility of a large cross section of USAF pilots to
canal sickness, using Wright-Patterson Air Force Base centrifuge

facilities under the sponsorship of the Aerospace Medical Laboratory (Refs 7, 18).

       (2) Theoretical Studies (Human factors and/or engineering aspects)

            (a) Living-working compartment design.

            (b) Closed Ecological System design.

            (c) Display and control requirements for mission accomplishment.

            (d) Vehicle rotational stability and control.

            (e) Vehicle structural problems.

            (f) Space environment and nuclear power source radiation shielding requirements.

            (g) Escape vehicle requirements.

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